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AIRCRAFT FUEL HEAT SINK UTILIZATION

C.N. Gray
M.W. Shayeson

General Electric

TECHNICAL REPORT AFAPL-TR-73-51

JULY 1973

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AIRCRAFT FUEL HEAT SINK UTILIZATION

C.N. Gray
M.W. Shayeson

FOREWORD

This report was prepared by the Advanced Engineering and Technology Programs Department and the Material and Process Technology Laboratories of the General Electric Aircraft Engine Technical Division, Evendale, Ohio under Contract F33615-72-C-1715. The program was jointly funded under Projects 3048 and 3066 (Tasks 304805 and 306603). This contract was monitored by the Air Force Aero Propulsion Laboratory with Royce P. Bradley and Captain William L. Noll as Air Force Project Engineers.

This report covers the period from 14 April 1972 to 14 April 1973 and was submitted by the authors on 15 May 1973.

This technical report has been reviewed and is approved.

Arthur V. Churchill
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Air Force Aero Propulsion Laboratory

ABSTRACT

This report identifies fuel temperature levels and contributors to fuel temperature rise or decrease at each step of fuel handling or usage from ground bulk storage to engine combustor. The program consisted of a literature search and review of available information on fuel temperatures in bulk storage and on-loaded aircraft tanks, flight profile effects on fuel tank fuel temperature, and fuel temperature changes resulting from aircraft and engine heat loads in flight. The study program was supplemented by MINEX thermal stability tests on JP fuels supplied by the USAF. The results indicate a low incidence of bulk storage or refueling fuel temperatures above 95° F. Aircraft wing tank fuel temperatures, in static ground soak and in flight, follow closely the changes in local ambient or free stream total temperature. Fuselage or body tank fuel temperatures, in static ground soak or in flight, have a gradual change with respect to large differences in local ambient or free stream total temperature. The sources and levels of heat loads from aircraft and engine are established. Fuel temperatures are significantly influenced by the power requirements, the environment, and the design for thermal integration of the engine and aircraft fuel systems. The results of the MINEX thermal stability tests show a wide range in relative quality level for the fuels tested. The overall results indicate that aircraft and engine systems can be designed to operate in the Mach 3 range using present primary type fuels and state-of-the-art fluid system components. Heat loads must be established in the early stages of conceptual design making aircraft fuel heat sink utilization a key consideration in the design of future high performance aircraft.

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SECTION I

INTRODUCTION

The development of highly sophisticated aircraft has created an increasing need for aircraft and engine systems cooling capacity. Airborne electronic equipment and environmental systems cooling needs, in addition to aircraft flight control systems, have created an increasing need for cooling capacity (i.e., heat sink). This is true in subsonic and subsonic/supersonic dash or supersonic cruise aircraft. The aircraft fuel is a major source of coolant and is relied on heavily by aircraft and engine designers to avoid use of air-to-air or other auxiliary heat exchangers to provide airframe and engine systems cooling.

While the aircraft demands on the fuel heat sink have increased, the engine cycle efficiency has improved thereby reducing the amount of fuel flow to the engine combustor available for cooling purposes. To further complicate the problem, the fuel temperature rise sources within the engine fuel system have remained constant or have increased due to higher engine pressure ratios.

The mission requirements for present development and future high performance aircraft require engine operation over a broad range of altitudes and flight Mach numbers. The augmented multispool turbofan or turbojet has evolved in order to satisfy these requirements. As a result, engine heat loads (Btu/minute transferred to the engine lube oil) have increased because multispool engines of necessity have more engine bearings and consequently generate more heat to be rejected to the lubricating oil. This combination of operating requirements and specific design has resulted in a situation where the heat sink capacity of the fuel is heavily taxed, with supplementary cooling often a requirement.

For those applications of supersonic dash or supersonic cruise where no cool air source is available, the aircraft fuel heat sink capacity is then one of increasing demand limited by a diminishing, varying, and arbitrary flow quantity. The problem may be further compounded by design practices which assume a worst-temperature stackup condition at the engine inlet in order to ensure heat sink availability for aircraft systems use. Across-the-board maximum inlet fuel temperature design requirements may ignore aircraft and engine operating condition variations, peak aircraft/engine heat load match or mismatch, and percent of engine operating time at various inlet temperature levels. The result of this is a minimization of heat sink available within the engine fuel system for cooling purposes.

Another boundary on fuel heat sink capacity is the maximum allowable fuel temperature at the inlet to the engine combustor. The upper design limit of fuel temperature for the present primary fuels, JP-4 and JP-5, and their commercial counterparts (Jet A, Jet A-1, and Jet B), generally is considered to be about 325° F delivered to the combustor. This temperature has been demonstrated to be a satisfactory limit for reasonable operating times, using

these jet fuels, and is based on known thermal stability characteristics of typical fuel batches. Above 325° F some fuel batches will exhibit gumming, varnishing, or coking to various degrees, causing fuel nozzle degradation and fuel heat exchanger and other hot section distress. Many primary jet fuel samples have demonstrated thermal stability to much higher temperatures in small scale testing devices. However, the present primary jet fuel specifications are established to avoid restrictive properties as much as possible. This procedure is established to benefit logistics and to maintain minimum unit cost of fuel consistent with satisfactory performance.

The efforts on this study program were directed toward determination of fuel temperature level and contributors to fuel temperature rise or decrease at each step of the fuel usage process from ground bulk storage to engine combustor and to determine by MINEX thermal stability test the relative quality range of present day primary fuels.

SECTION II

FUEL STORAGE AND HANDLING

This section presents fuel temperature information for ground bulk storage and aircraft refueling as obtained from fuel temperature surveys at various USAF bases and commercial airports around the world. Included are maximum fuel temperature levels reached during maximum ambient temperature periods, as well as data analysis and data plots showing fuel temperature changes resulting from ambient temperature changes for periods of one month to one year.

From commercial sources, the Coordinating Research Council (CRC) published in a June 1964 report[1], a list of fuel temperatures at selected foreign locations, as shown in Table I. This illustrates that the temperature of fuel in storage and into aircraft approaches atmospheric temperatures. In the same report, the CRC presented a listing of the distribution of fuel temperatures both in the ground fueler and in the aircraft after loading, as analyzed by a major U.S. domestic airline for the year 1963. These typical data are as follows:

	Percent of Time	
	In the Fueler	In the Aircraft
Above 95° F	1	<1
Above 80° F	23	7
Above 60° F	63	45
Above 32° F	95	87

The fuel temperature data from these commercial sources indicates a low incidence of on-loaded fuel above 95° F.

From military sources, fuel temperature information from six selected USAF bases covering a range of ambient temperature from +116° F to -25° F is used to establish fuel temperature profiles in ground storage tanks and in refueling equipment.

Maximum fuel temperature levels for ground storage tanks and refueling equipment are of prime importance, and Figure 1 shows the monthly maximum fuel temperature levels recorded for Loring[2], Edwards[2], and Luke[2] Air Force bases for one-year periods. Also shown in Figure 1 are the monthly maximum and minimum ambient temperature levels recorded over the same time periods. It is important to note that the monthly maximum temperature levels (and minimum for ambient) in many cases occur during only one specific day during the month. Aircraft refueling is accomplished primarily by hydrant system at Loring AFB and by truck at Luke AFB and Edwards AFB.

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[1] Numbers in parenthesis refer to similarly numbered references.

Table I. Fuel Temperature Survey*.

Country-Airport	Atmospheric Temperature, ° F	Storage Tank Temperature, ° F	Dispenser Equipment	Fuel Into Aircraft Temperature, ° F
Egypt				
Cairo	108	N.A.	Hydrant System	96
			Fueler	98
Greece				
Athens	108	97	Fueler	99
India				
Bombay	91	95	Hydrant System	95
Calcutta	99	94	Fueler	96
Delhi	111	102	Hydrant System	100
Kenya				
Nairobi	90	N.A.	Hydrant System	85
Lebanon				
Beirut	91	N.A.	Hydrant System	95
			Fueler	98
Philippines				
Manila	97	92	Hydrant System	
			Fueler	99
South Africa				
Johannesburg	97	74	Fueler	85
Spain				
Madrid	96	N.A.	Fueler	79
Thailand				
Bangkok	96	94	Hydrant and Fuelers	N.A.
Bahrain Island				
Muharrag	113	N.A.	Hydrant System	97
Pakistan				
Karachi	97	N.A.	Hydrant System	98
	105	105		-

*All temperatures shown are maximum temperatures.

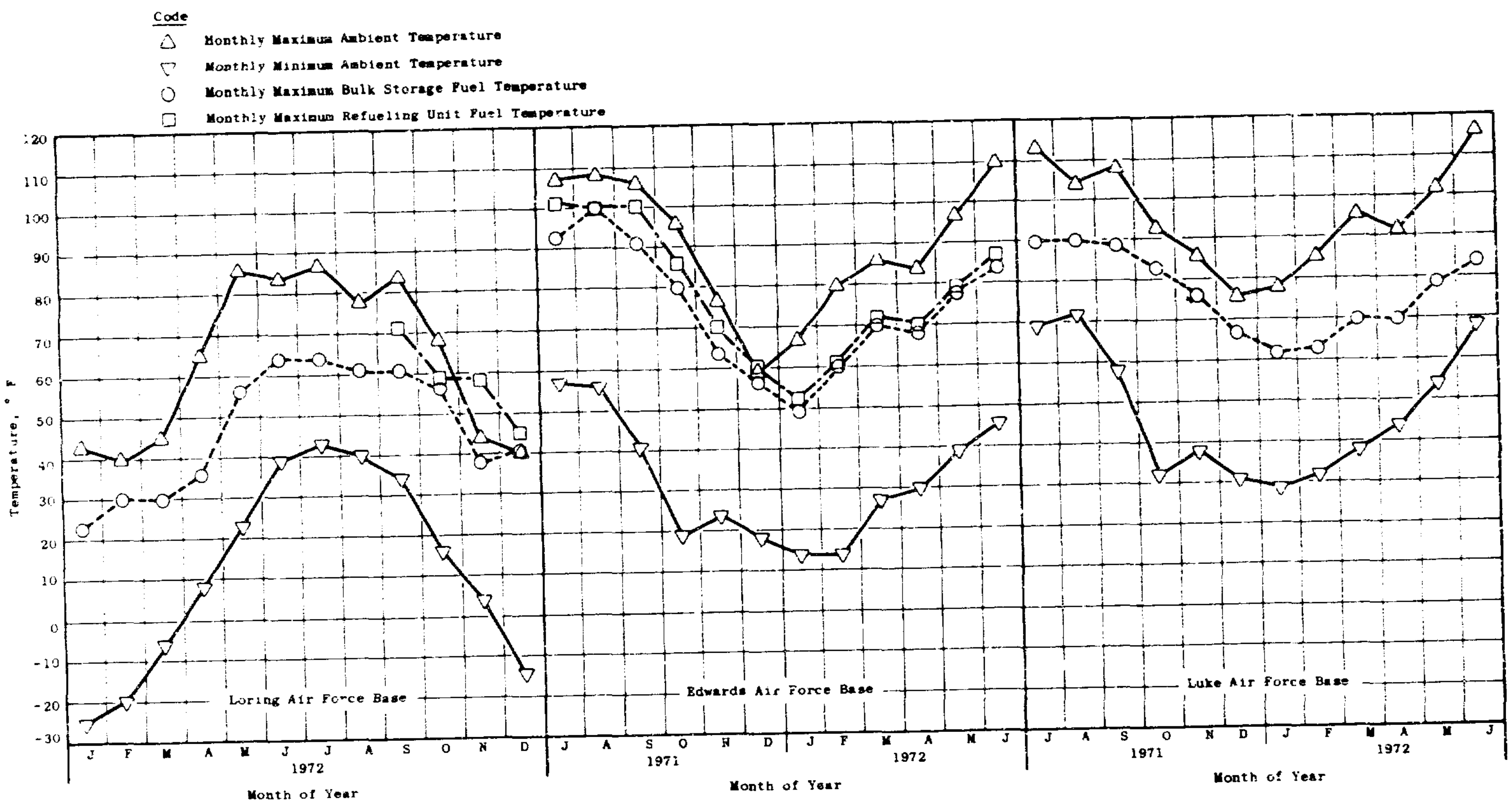


Figure 1. Monthly Maximum Fuel Temperature Levels.

The data plots in Figure 1 show that bulk storage and refueling fuel temperature levels are significantly influenced by ambient temperature levels, that monthly maximum fuel temperature levels are generally below monthly maximum ambient temperature levels, and that there is a low incidence of refueling fuel temperature above 95° F.

While maximum bulk storage and refueling fuel temperatures are of prime importance, it is also necessary to establish the trends in these fuel temperature levels as these levels are influenced by the daily changes in ambient temperatures.

Figures 2, 3, and 4 show the overall trends in fuel bulk storage and ambient temperature levels as obtained from Loring[2], Edwards[2], and Luke[2] Air Force Bases for periods of four months to one year. Also included for Edwards is refueling unit fuel temperature. The fuel and ambient temperature plots for these three figures were established by plotting the day-to-day levels of temperature and by drawing a smooth curve through the erratic ups and downs to establish the overall trends.

The data plots in Figures 2, 3, and 4 show that fuel temperatures are significantly influenced by ambient temperature levels. The overall trends in fuel temperatures follow the overall trends in ambient temperatures; however, the fuel temperature changes do not follow the short time limited changes in ambient temperature levels.

The daily changes in ambient temperature levels, and their effect upon fuel temperature levels, are shown by the data plots in Figures 5 and 6 which include temperature data from Howard[2] AFB and two South East Asia (SEA)[2] Air Force Bases. The fuel temperatures in these two figures show that the daily temperature changes in ground bulk storage and refueling units fall within a very narrow (approximately 5° F) band for the time periods indicated.

Figure 6 also includes fuel temperature information for on-loaded aircraft fuel temperature levels which will be discussed in Section III. For Figure 6, the fuel temperature measurements were taken from the upper level of storage tanks and refueling units, and from wing tank/drop tank sump drains of the respective aircraft. Fuel temperatures were taken during the warmest part of the day from units and from aircraft exposed to the sun since last filling/servicing. Also, it should be noted that the ambient air temperature was reported to be 85° to 90° F at these two SEA bases during January 1971.

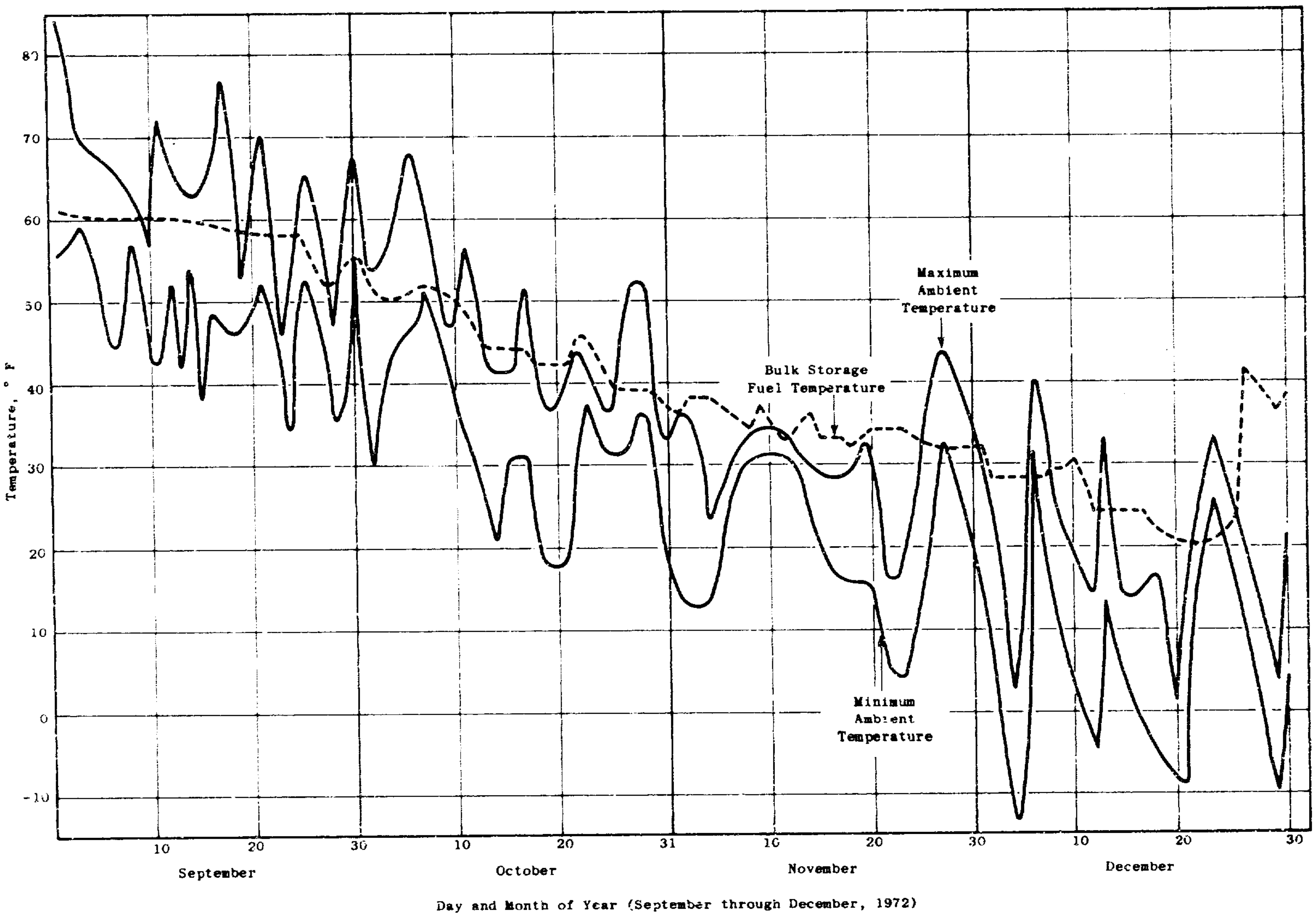


Figure 2. Bulk Storage Fuel Temperature, Loring Air Force Base.

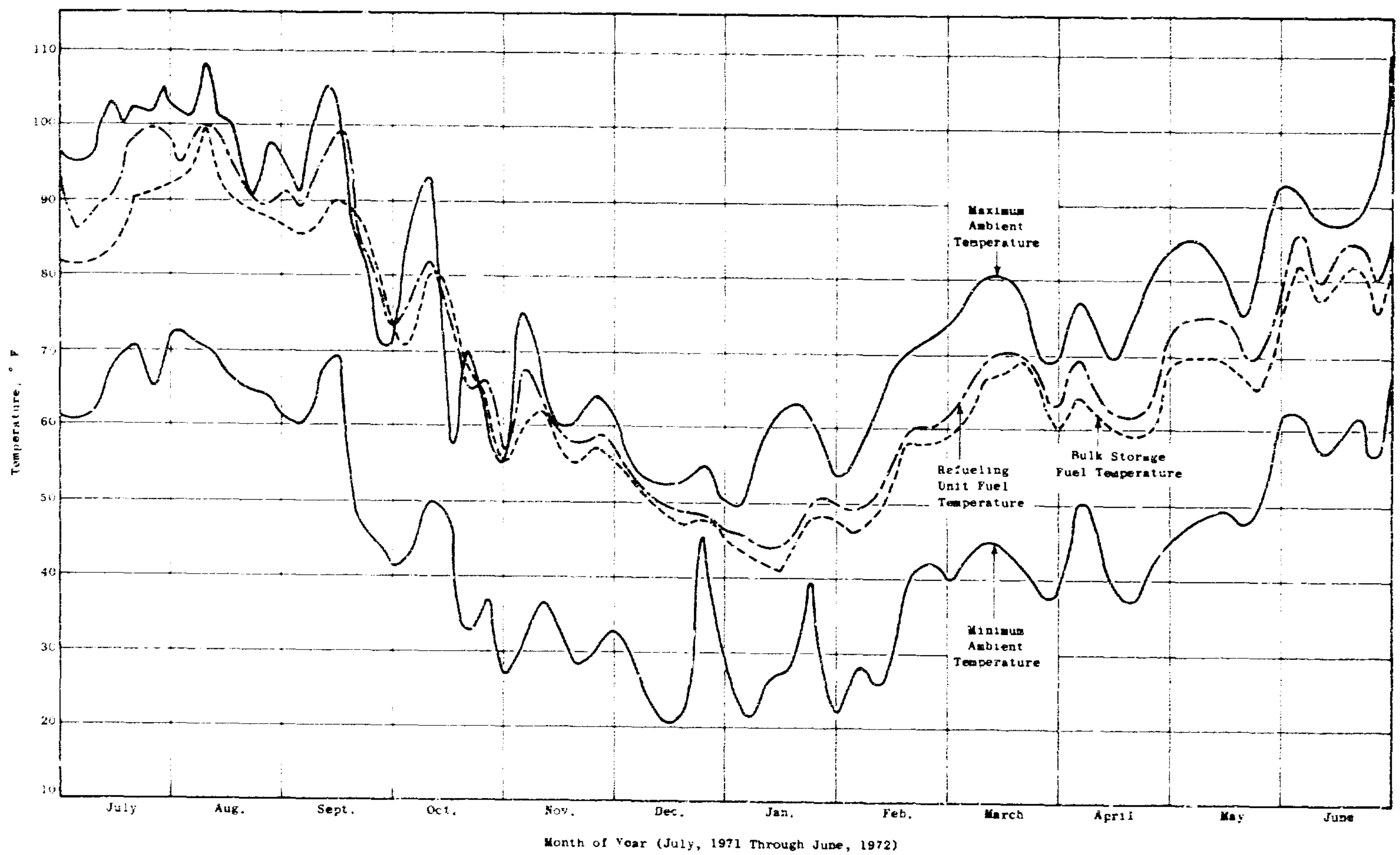


Figure 3. Bulk Storage and Refueling Unit Fuel Temperatures, Edwards Air Force Base.

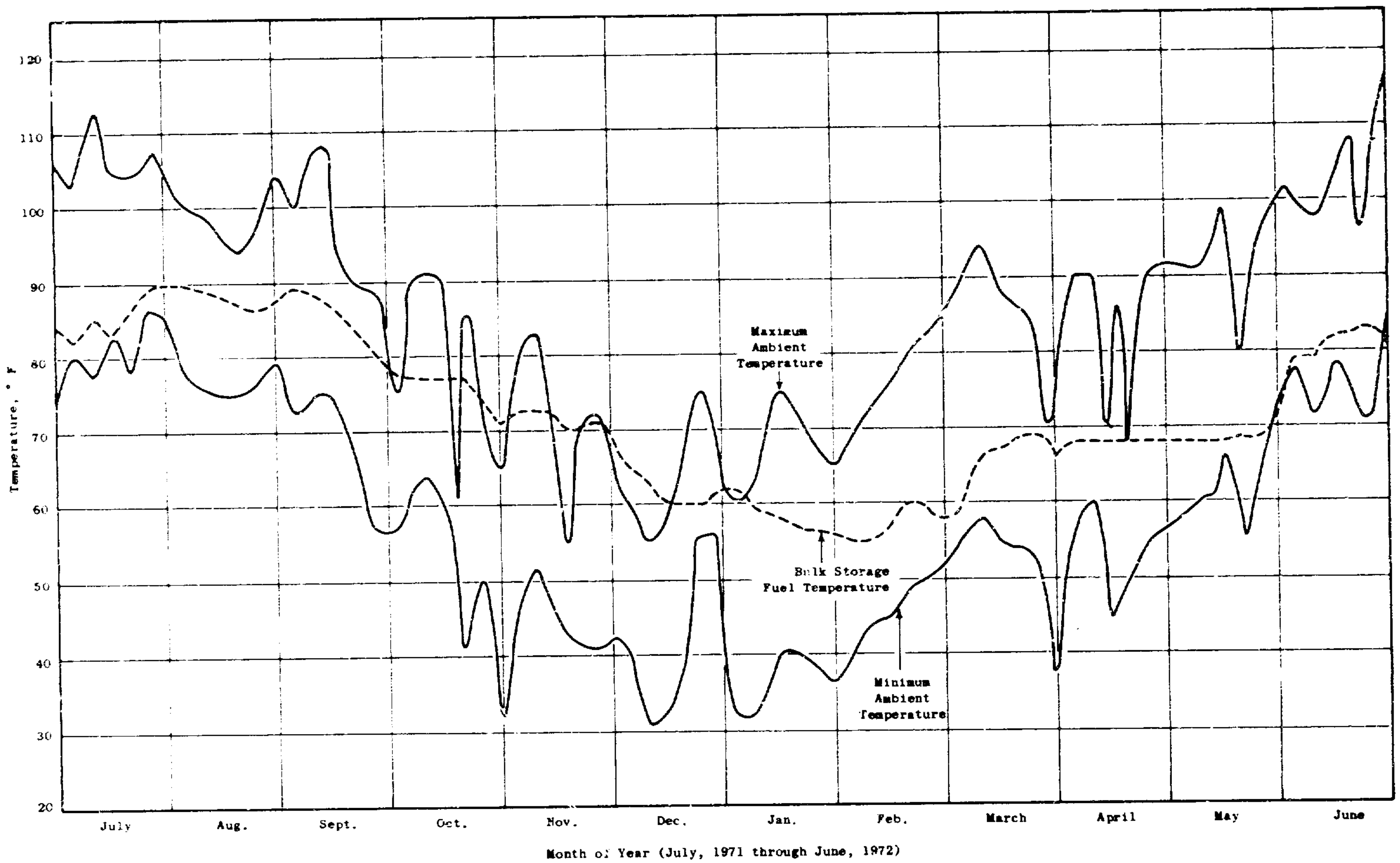


Figure 4. Bulk Storage Fuel Temperature, Luke Air Force Base.

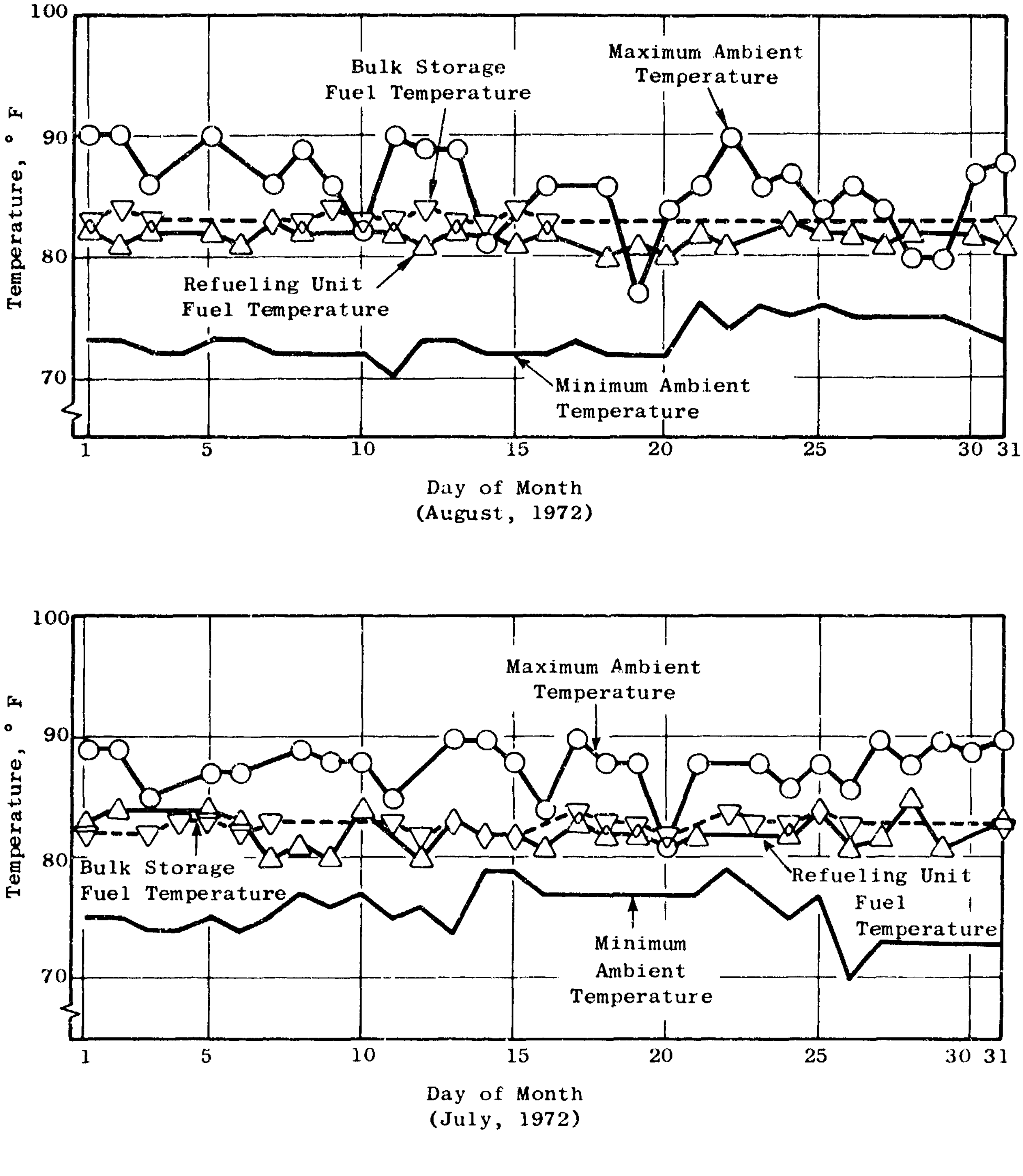
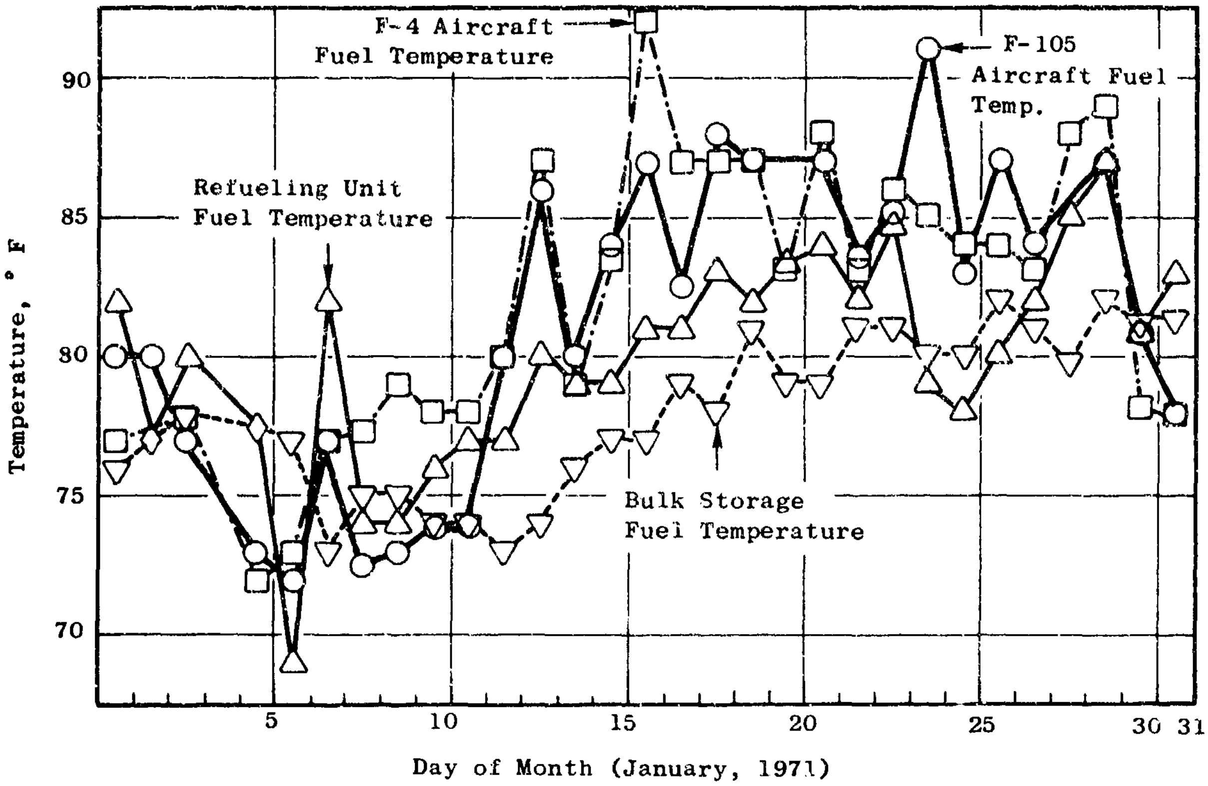


Figure 5. Bulk Storage and Refueling Unit Fuel Temperature, Howard AFB.



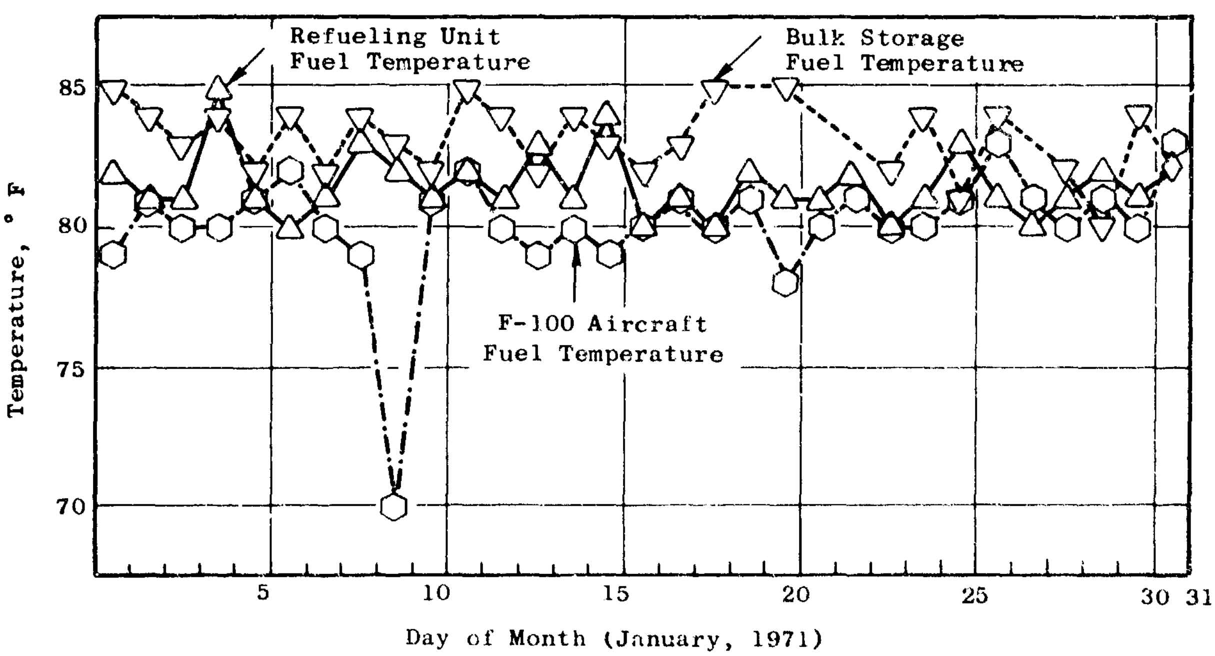


Figure 6. Bulk Storage Refueling Unit, Aircraft On-Loaded Fuel Temperature, Sea Air Force Base.

SECTION III

STANDBY AND READINESS

Fuel temperature changes in on-loaded aircraft fuel tanks (simulating aircraft on standby, alert, or readiness) are presented in this section. Included are results of temperature surveys on F-series aircraft in hot desert and cold arctic ambient temperature environments, and on static hot and cold soak tests of B- and C-series aircraft.

The temperature plots as shown on Figure 7 are the results of hot soak temperature surveys for the F-4C[3], F-5A[4], and F-111A[5] aircraft taken at the U.S. Marine Corps Air Station, Yuma, Arizona (during July 1964 for the F-4C and F-5A, and during July 1967 for the F-111A).

During these same time periods, flight tests on these F-4C, F-5A, and F-111A aircraft were conducted and preceded by a hot soak in increasing ambient temperature levels. The ambient temperature and the fuel cell fuel temperatures after hot soak and at takeoff are tabulated as follows:

Aircraft & Flight No.	Hot Soak Period, Hours	Take-Off Temperature, ° F	Left Wing Tank Fuel Temp, ° F	Fuselage or Trap Tank Fuel Temp, ° F
F-4C[3]				
1	4	111	109	103
7	4	115	110	101
9	4	108	104	98
F-5A[4]				
6	4	118	N/R**	99*
10A	N/R	106	N/R	99
F-111A[5]				
2	72	108	115	94
7	4	107	114	96
8	4	114	120	96

*The 4-hour ground hot soak data for this flight are plotted in Figure 22, Section IV.
** Not Recorded

During the hot soak test periods, as shown on Figure 7, ambient temperature levels at the ramp were recorded from ground level to the 14/15 foot level. For the F-4C and F-5A aircraft, the ambient temperatures at the 3-, 6-, and 9-foot levels fell generally within 2° to 3° F of each other.

The F-4C plots on Figure 7 show that fuel temperature in the left wing tank follows closely the 3- to 9-foot ambient temperature cycle and peaks

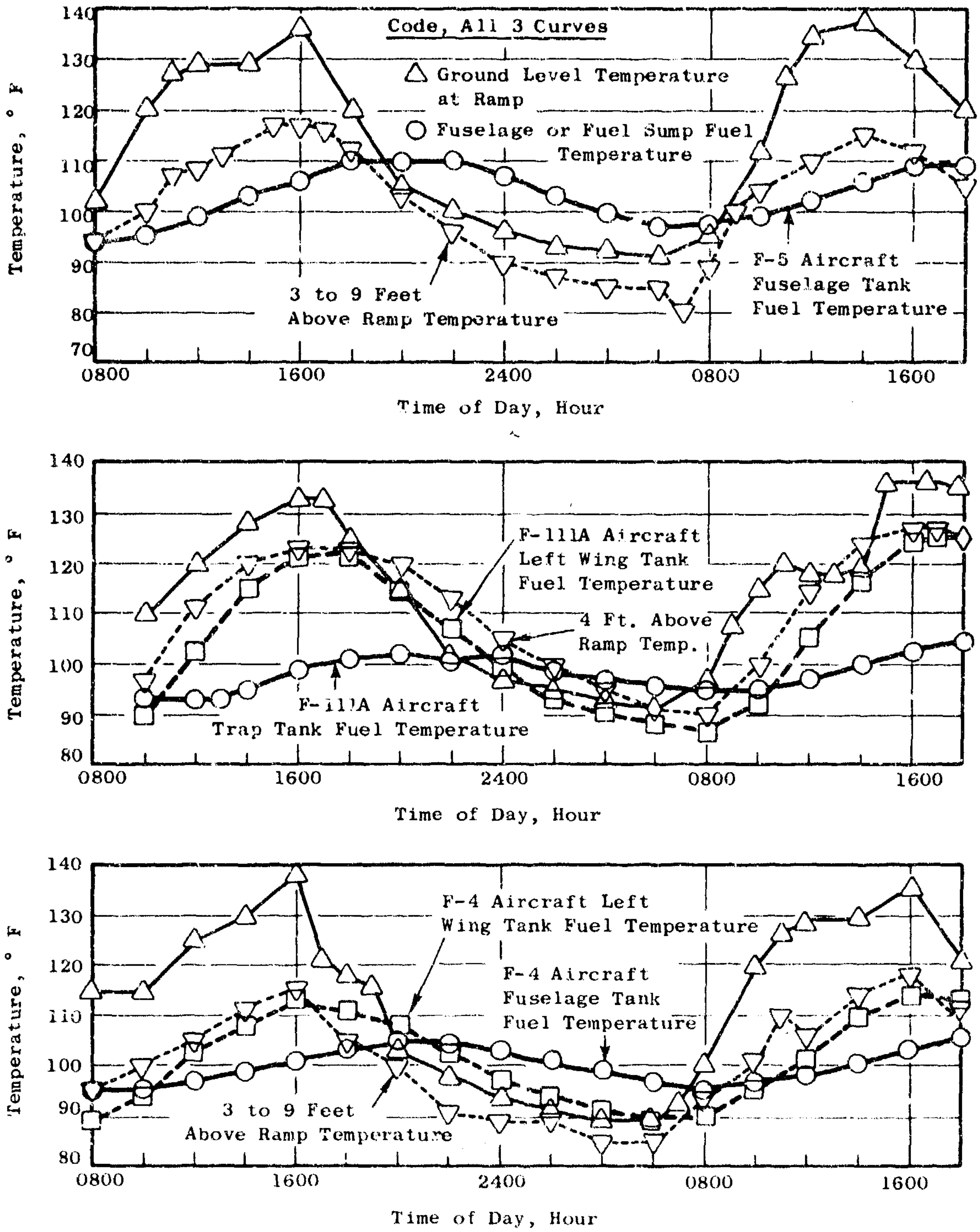


Figure 7. Hot Soak Temperature Survey on F-4, F-5 and F-111A Aircraft.

2° to 4° F below the ambient peak. The F-4C data for the hot soak prior to flight also shows that the left wing fuel temperatures are 2° to 5° F below the take-off ambient temperature.

The F-111A plots on Figure 7 show that the fuel temperature in the left wing tank follows closely the 4-foot ambient temperature cycle and peaks at approximately the same ambient temperature level. The F-111A data for the hot soak prior to flight shows that the left wing tank fuel temperatures are 6° to 7° F above the take-off ambient temperatures.

Figure 6 shows fuel temperatures as measured at the sump drains in wing tank/drop tanks for the F-4, F-100, and F-105 aircraft during January 1971 at two SEA bases. The data plots show that the fuel temperatures in wing and drop tanks follow the changes in bulk storage and refueling unit fuel temperatures.

Figure 7 shows that fuel temperatures in fuselage or trap tanks (for the F-4C, F-5A, and F-111A) lag and follow local cyclic ambient temperature changes; however, they reach peak levels below the peak ambient temperatures. The tabulations of fuselage or trap tank fuel temperatures also show that fuel temperatures are below the take-off ambient temperature level. A comparison of these temperature data showing the degrees F below the peak 3-to-9 or 4-foot ambient temperature levels of Figure 7, or the take-off temperature from the hot soak tests prior to flight, is as follows:

Ambient to Fuselage Tank Fuel Delta Temperature

	F-4C	F-5A	F-111A
Figure 7	10° to 12° F	6° to 7° F	20° to 22° F
Tabulation	8° to 14° F	7° to 19° F	11° to 18° F

These data for fuel temperature levels in fuselage or trap tanks show that the fuel temperatures are below ambient temperature levels.

The temperature plot as shown on Figure 8 is the result of a cold soak temperature survey on the F-4C[6] aircraft taken at Eielson AFB, Alaska, on 10 February 1964. The survey was conducted to measure the cool-down rate of the F-4C and its components during a typical overnight cold soak and shows the cooling rates of fuel in fuselage and left wing fuel tanks.

During the same time period, flight tests on the F-4C were conducted and were preceded by cold soak tests. During February 1967, flight tests were conducted on an F-111A aircraft at Eielson AFB and these flight tests were preceded by cold soak tests. The fuel temperature levels, in the wing tanks and the fuselage or trap tanks after cold soak and prior to take-off, are tabulated as follows:

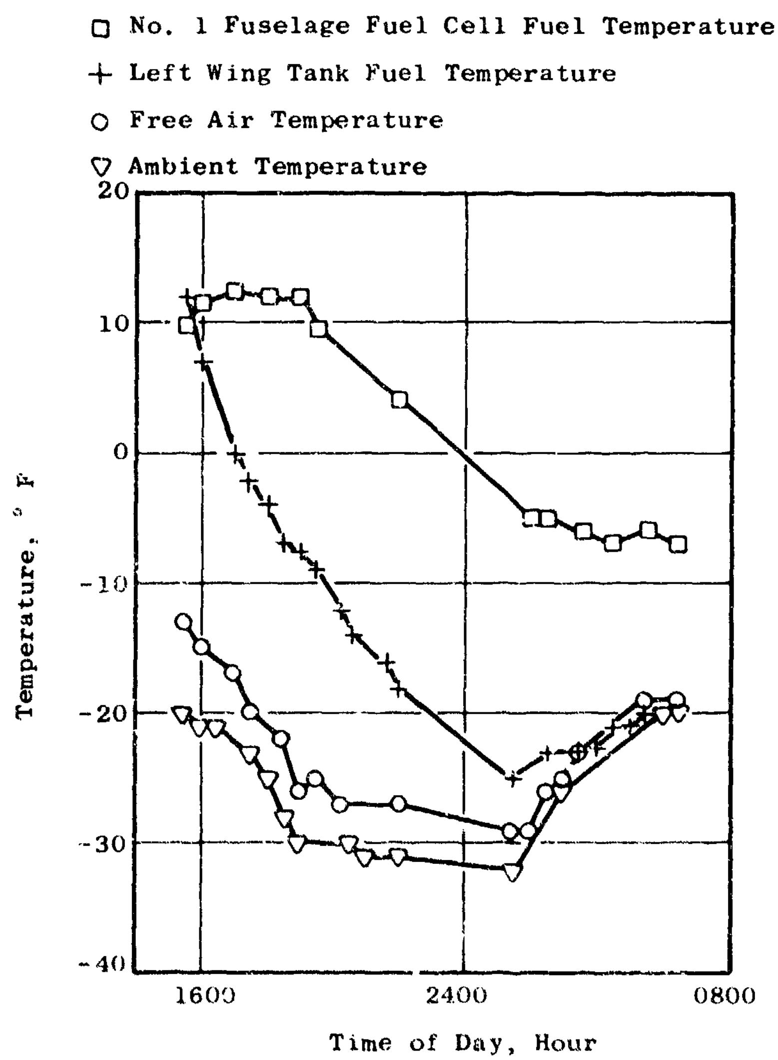


Figure 8. F-4C Cold Soak Temperature Survey.

Aircraft & Flight No.	Cold Soak Period, Hours	Temperatures at Aircraft Takeoff: Ambient Temp, °F	Left Wing Tank Fuel Temp, °F	Fuselage or Trap Tank Fuel Temp, °F
F-4C				
5	44	-6	-4	-5
8	33	-30	-23	-16
13	60	-30	-33	-26
F-111A				
2	36	-12	-22	-10
3	16	-19	-18	-1

The data (as shown on Figure 8 and in the tabulation) show that, for long cold soak periods, fuel temperatures in aircraft wing fuel tanks approach ambient temperature.

The results of static hot and cold soak temperature surveys on the B-52[2] aircraft are shown on Figure 9. For the static hot survey, the aircraft was cold soaked for a period of nine days and then entered a heated dock. Fuel temperatures in the fuel tanks, upon entering the heated dock, were approximately 10° F. For the static cold survey, the aircraft was in a heated dock for six days and was then subjected to cold ambient temperatures. Fuel temperature in all tanks, with the exception of the drop tank, was approximately 60° F. The drop tank was empty during the hot soak period and was fueled after the cold test was started with 31° F fuel.

The results of a static cold soak temperature survey on a KC-135[2] aircraft are shown in Figure 10. The static test conditions for this survey were extreme cold, low relative humidity, no wind, and no solar radiation.

The data plots shown in Figures 9 and 10 give an indication of the rate of temperature change of jet fuel in the wing tanks of B- and C-series aircraft under hot and cold static soak conditions. However, a comparison of these rates to actual weather conditions may not be realistic unless humidity, wind, and solar radiation variables are considered.

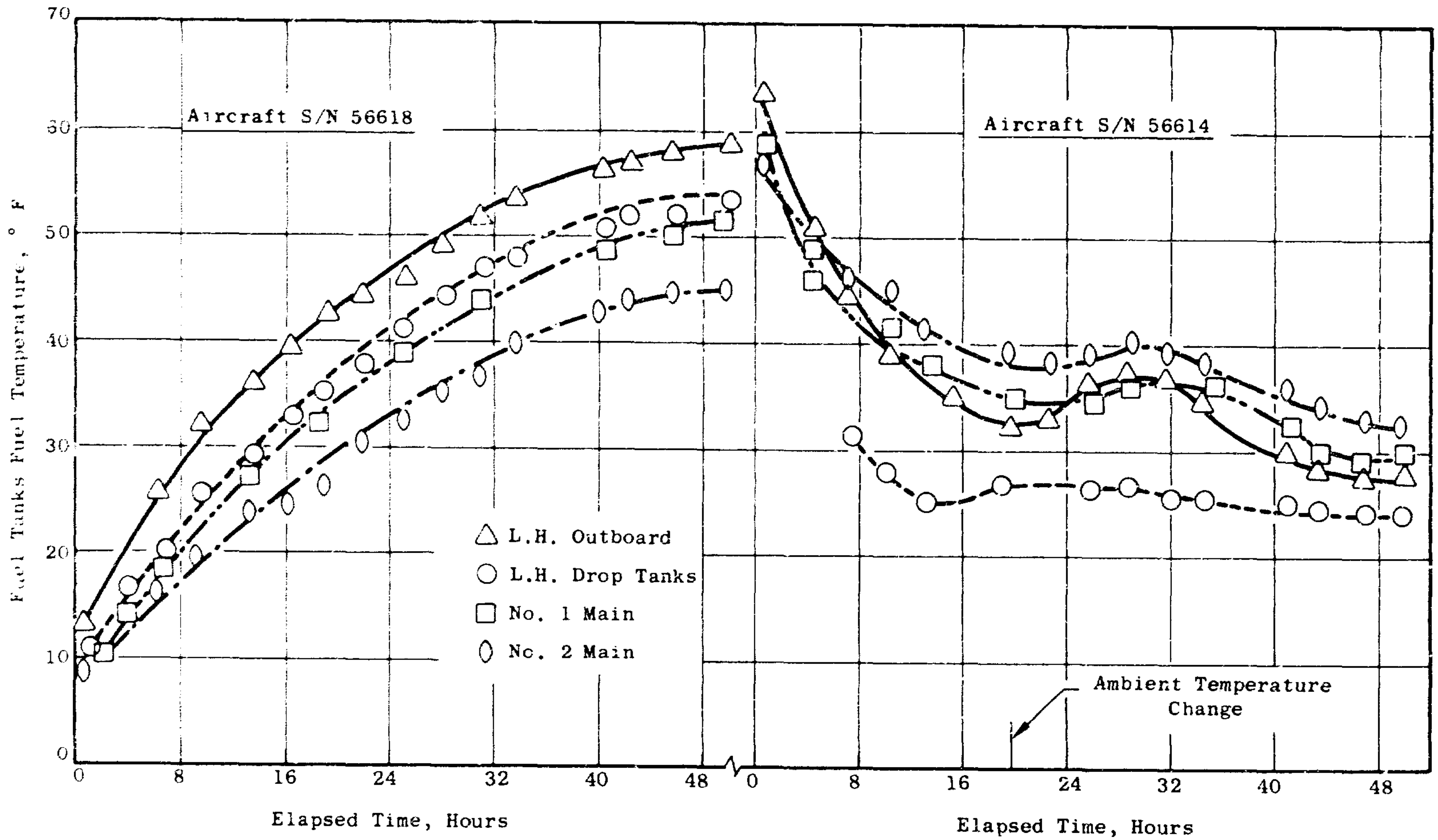


Figure 9. B-52 Hot and Cold Soak Temperature Survey.

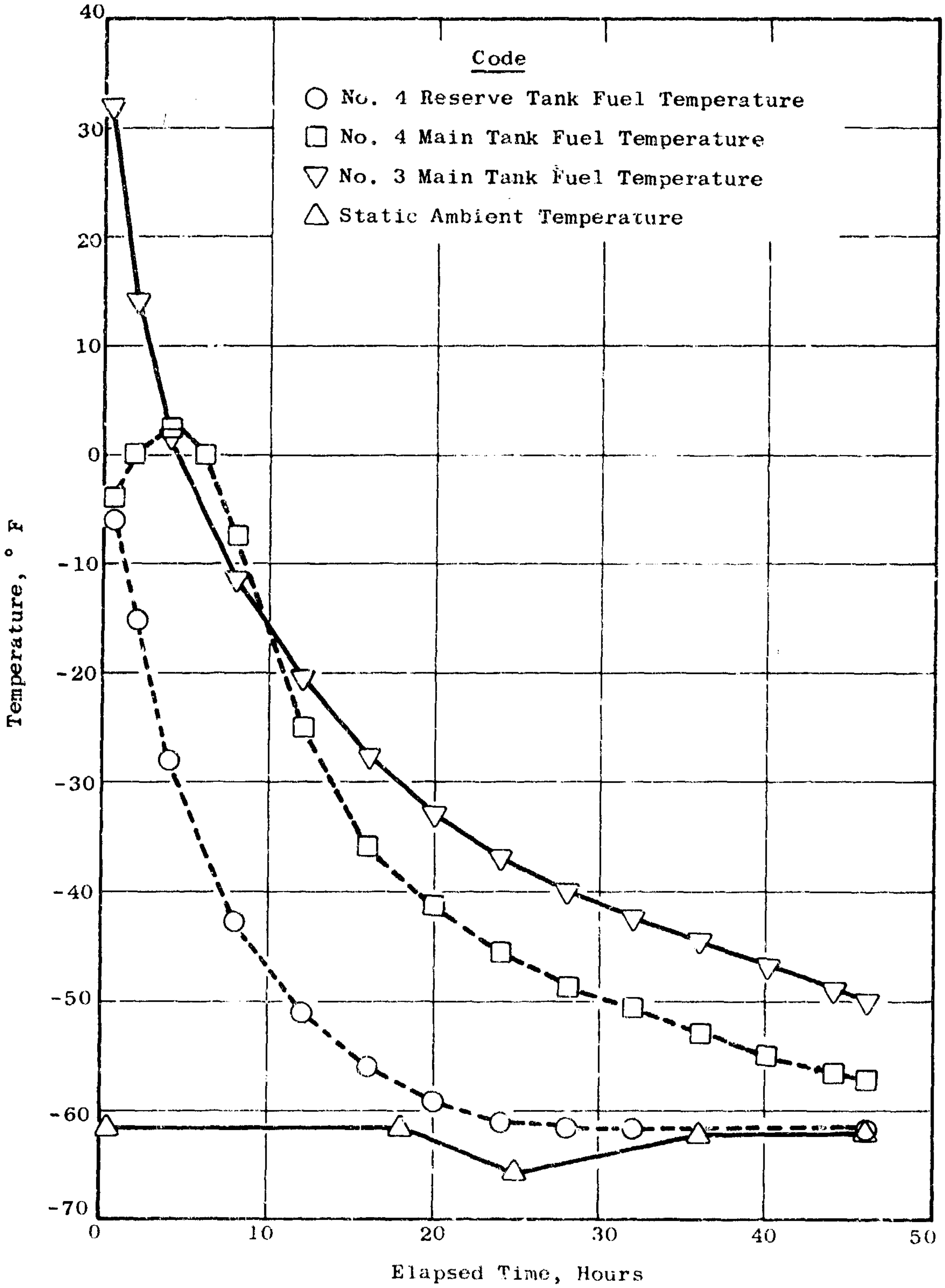


Figure 10. KC-135 Static Cold Soak Temperature Survey.

SECTION IV

FLIGHT PROFILE EFFECTS ON FUEL TANK FUEL TEMPERATURE

This section presents information on flight profile effects on fuel temperature in aircraft fuel tanks. Data plots are included for B-, C- and F-series aircraft after takeoff from hot desert locales with take-off ambient and fuel temperatures approaching +130° F to takeoff from cold arctic locales with take-off ambient and fuel temperatures approaching -30° F.

Figures 11, 12, and 13 show the changes in fuselage and wing tank fuel temperatures over a range of flight altitudes for the F-4C[3] during tests under desert high temperature conditions at the U.S. Marine Corps Air Station, Yuma, Arizona, during the period 13 July through 16 August 1964. Prior to each of the flights, the aircraft was hot soaked for four hours.

Figures 14, 15, and 16 show the changes in fuselage and wing tank fuel temperatures over a range of flight altitudes for the F-4C[6] during tests under arctic low temperature conditions at Eielson AFB, Alaska, during the period 5 January through 17 February 1964. Prior to each of the flights the aircraft was cold soaked from 33 to 60 hours.

Analysis of the temperature data as shown on Figures 11 through 16 indicated that fuel temperature in the F-4C aircraft fuel tanks is a function of take-off fuel temperature and aerodynamic heating or cooling of the resulting total free air temperature.

The overall fuselage tank fuel temperature cooling rates for Figures 11 through 13 vary from 0.3° F per minute for Figure 11 (with an average temperature difference of 45° F between fuselage tank fuel temperature and total free air temperature), to 0.33° F per minute in Figure 13 (with an average delta temperature of 62° F), and 0.58° F per minute in Figure 12 (with an average delta temperature of 80° F). The heating rates of fuel in fuselage tanks as determined from the second flight segment in Figure 13 is approximately 0.65° F per minute for a delta temperature of approximately 40° F.

Wing tank fuel temperature cooling rates for Figures 11 through 13 have high initial rates of 3° to 4° F per minute and stabilize at the levels of total free air temperature. It should be noted that the quantity of fuel in wing tanks was not monitored and, therefore, the fuel temperatures during the latter parts of the flights are questionable.

Figures 14, 15, and 16 show the flight profile effects on F-4C fuel tank temperatures after takeoff from a cold arctic environment. The changes in tank fuel temperatures during these flights are limited due to the flight ambient total air temperature being within the same range as the take-off fuel temperatures.

Figures 17, 18, and 19 show the changes in trap tank and wing tank fuel temperatures over a range of flight altitudes for the F-111A[5] during tests under desert high temperature conditions at U.S. Marine Corps Air Station, Yuma, Arizona, during the period 22 June to 27 July 1967. Prior to each of the flights the aircraft was hot soaked for from 4 to 72 hours.

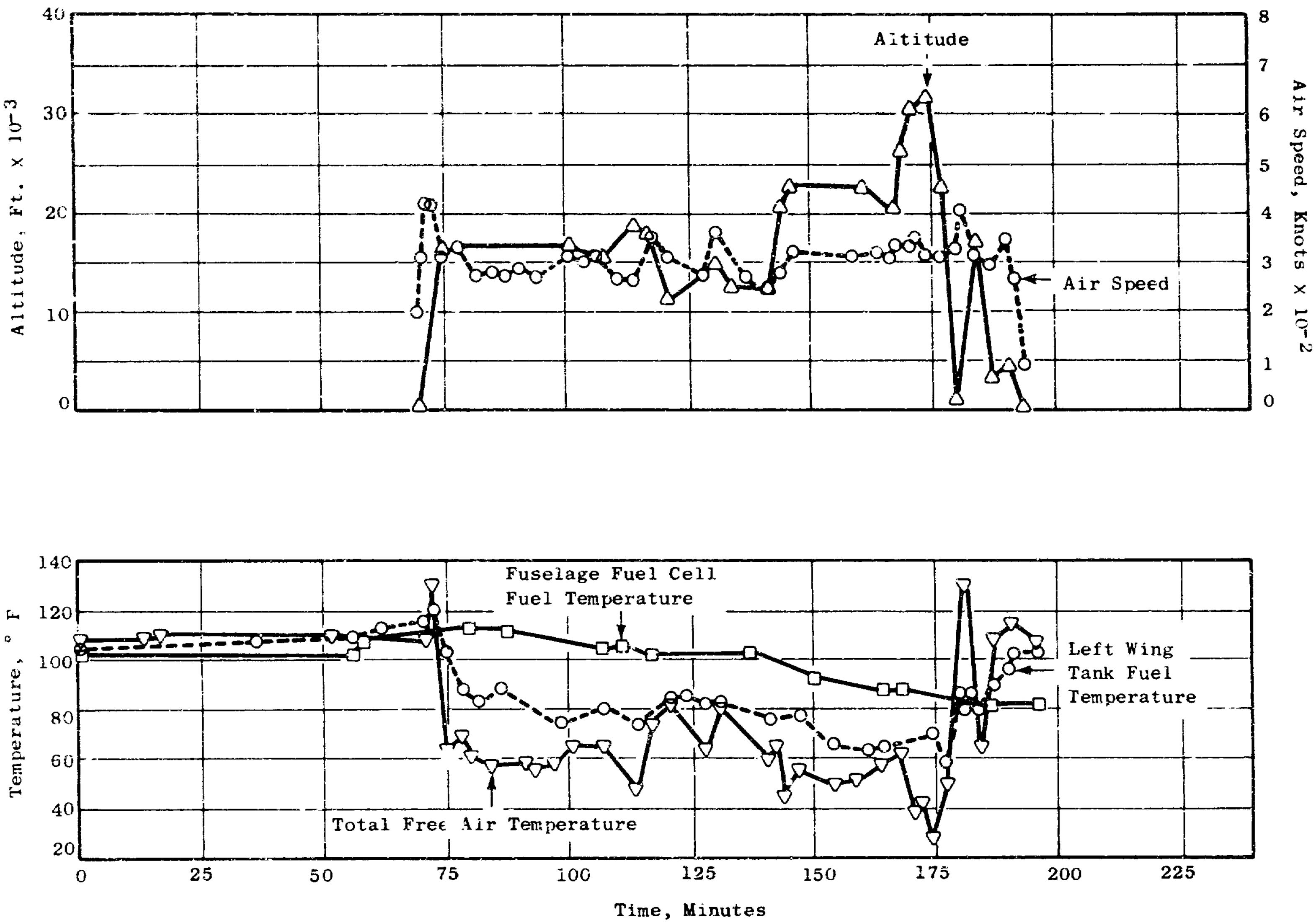


Figure 11. F-4C Fuel Temperatures in Flight.

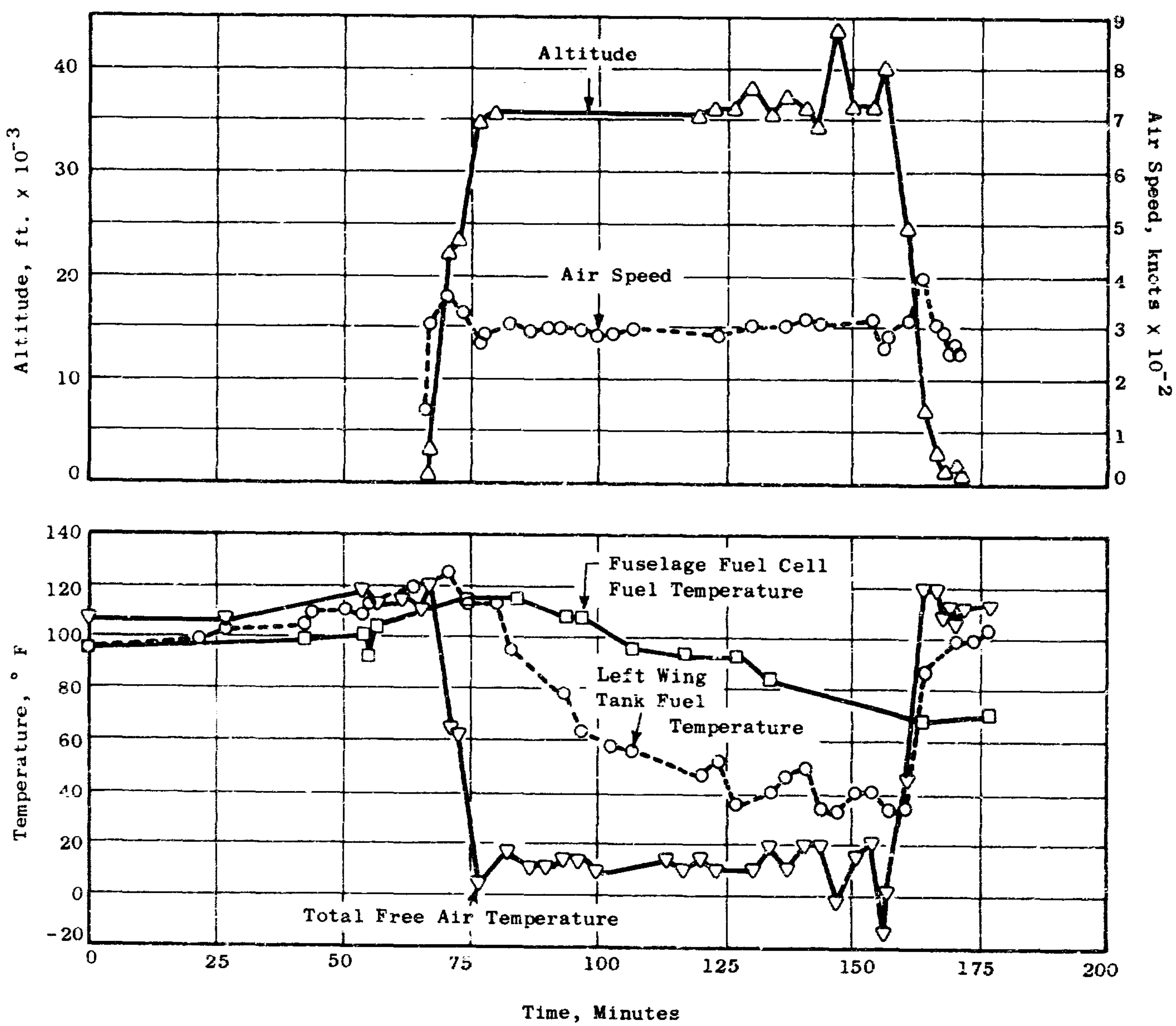


Figure 12. F-4C Fuel Temperatures in Flight.

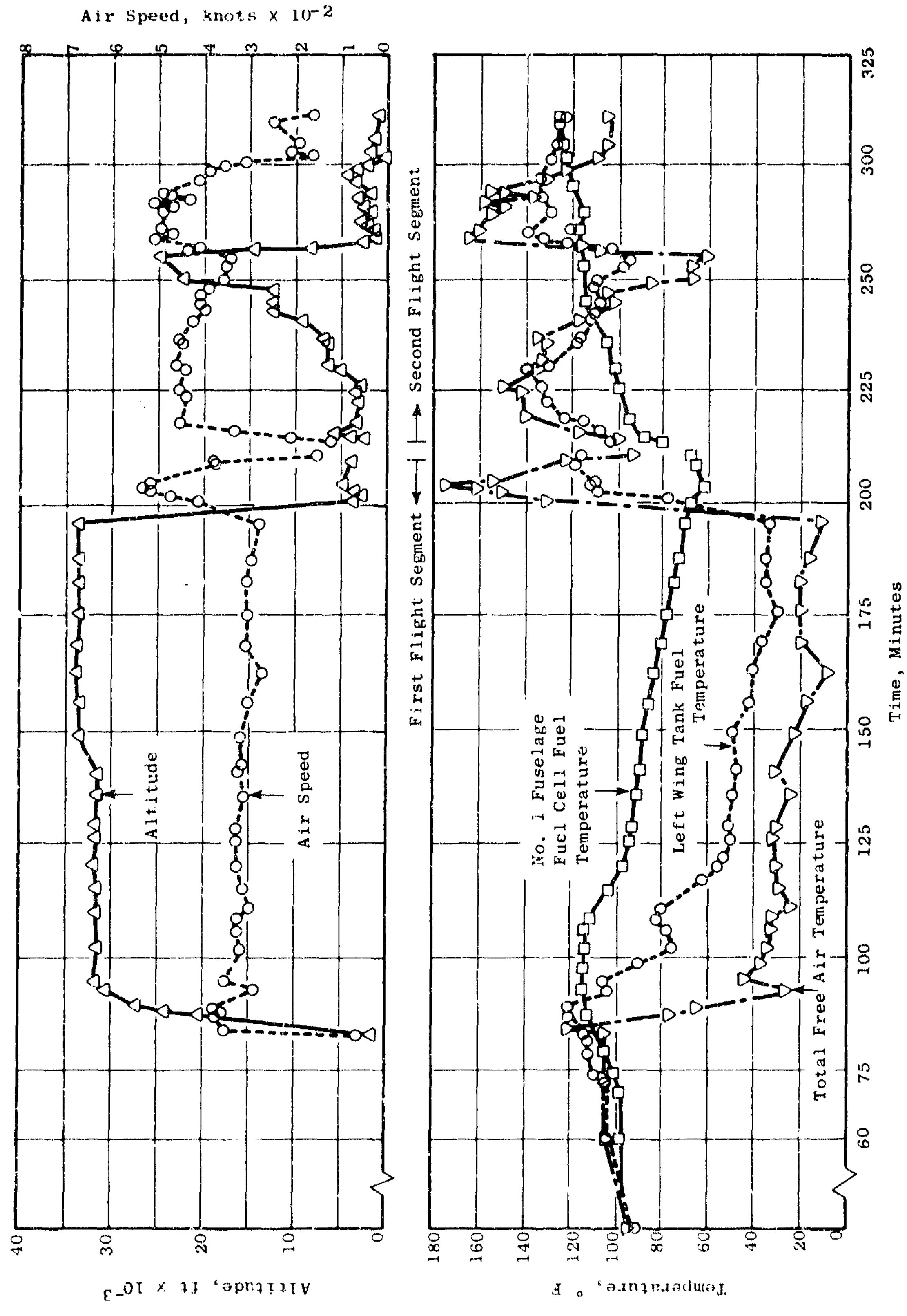


Figure 13. F-4C Fuel Temperatures in Flight.

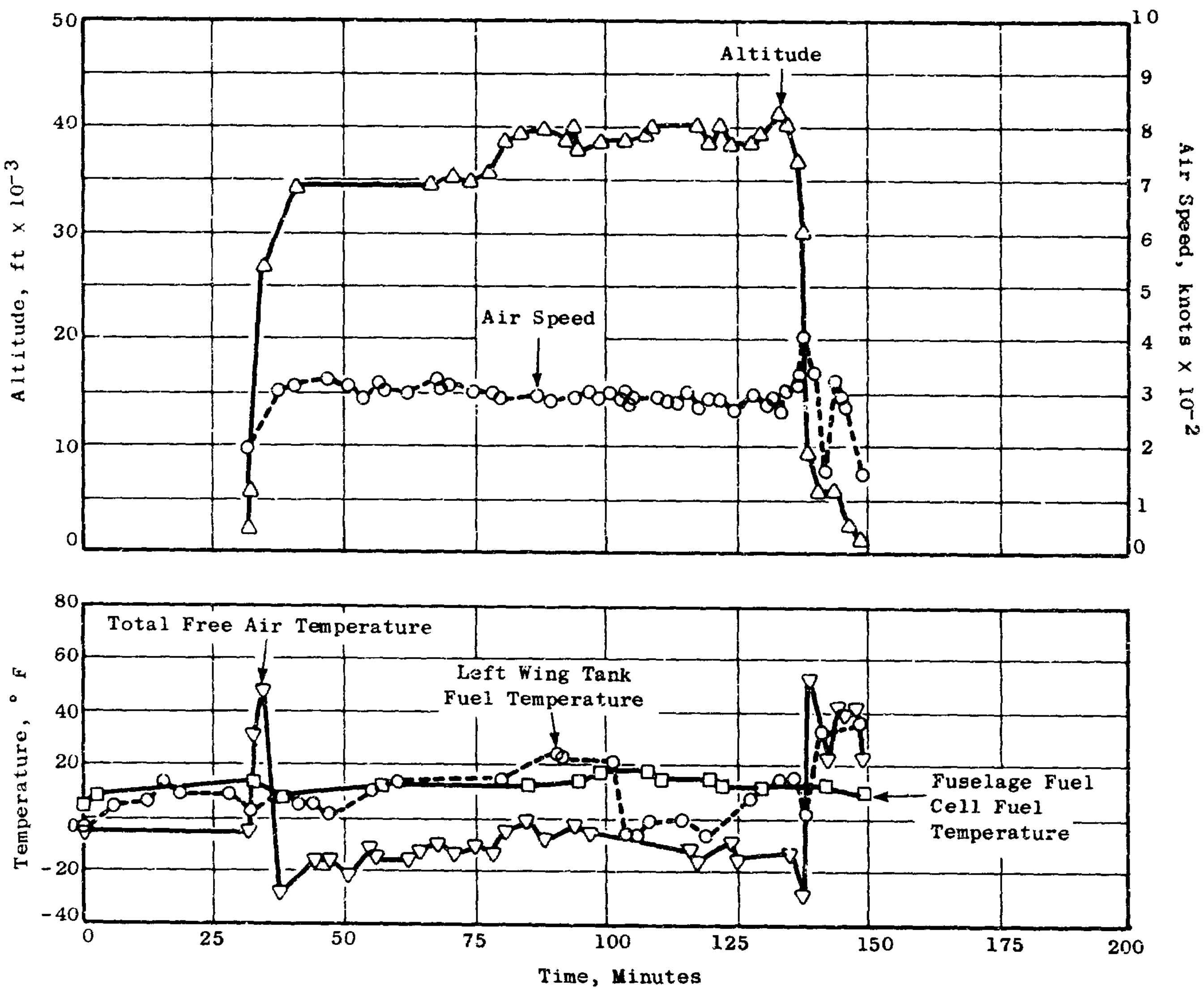


Figure 14. F-4C Fuel Temperatures in Flight.

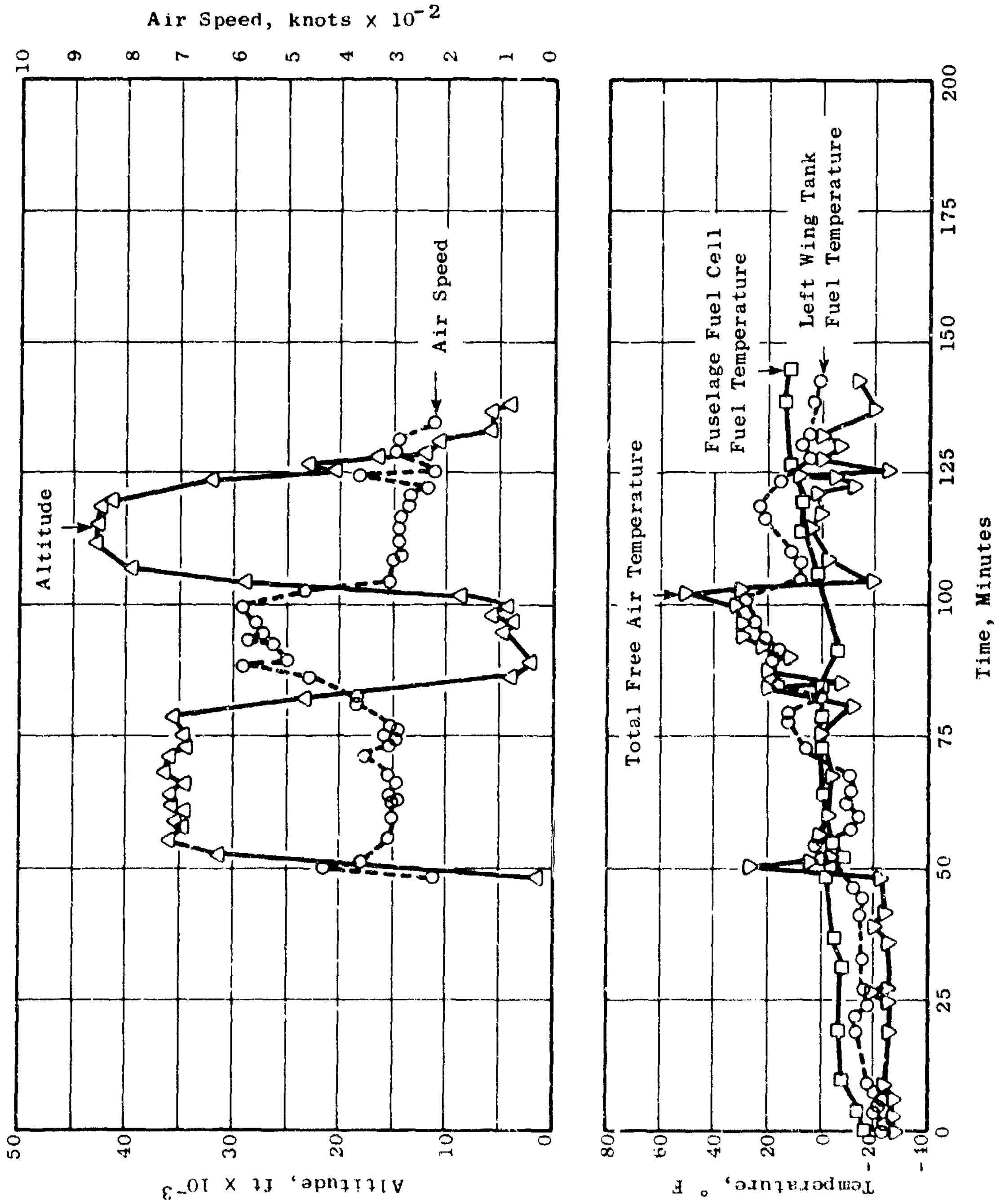


Figure 15. F-4C Fuel Temperatures in Flight.

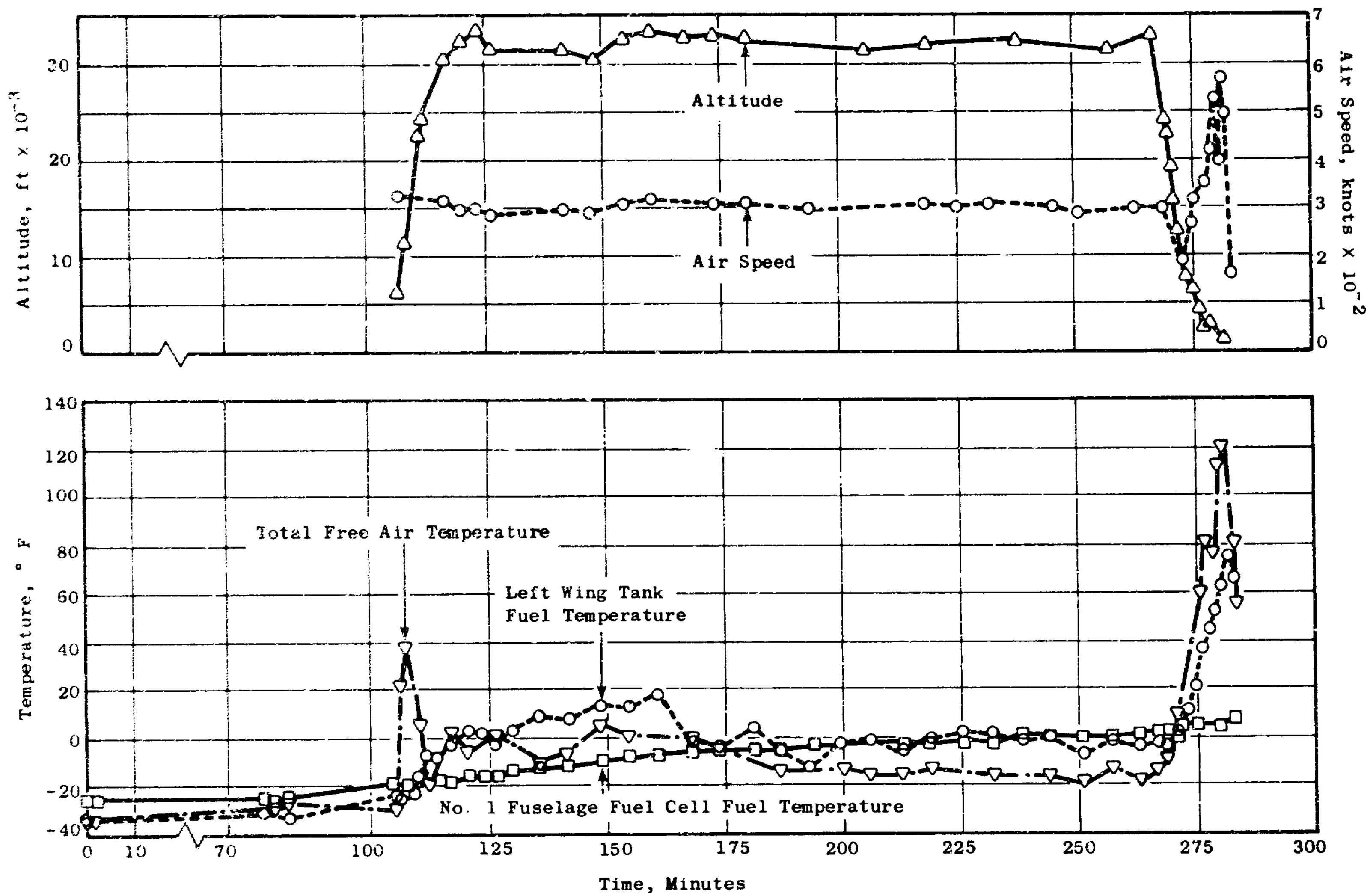


Figure 16. F-4C Fuel Temperatures in Flight.

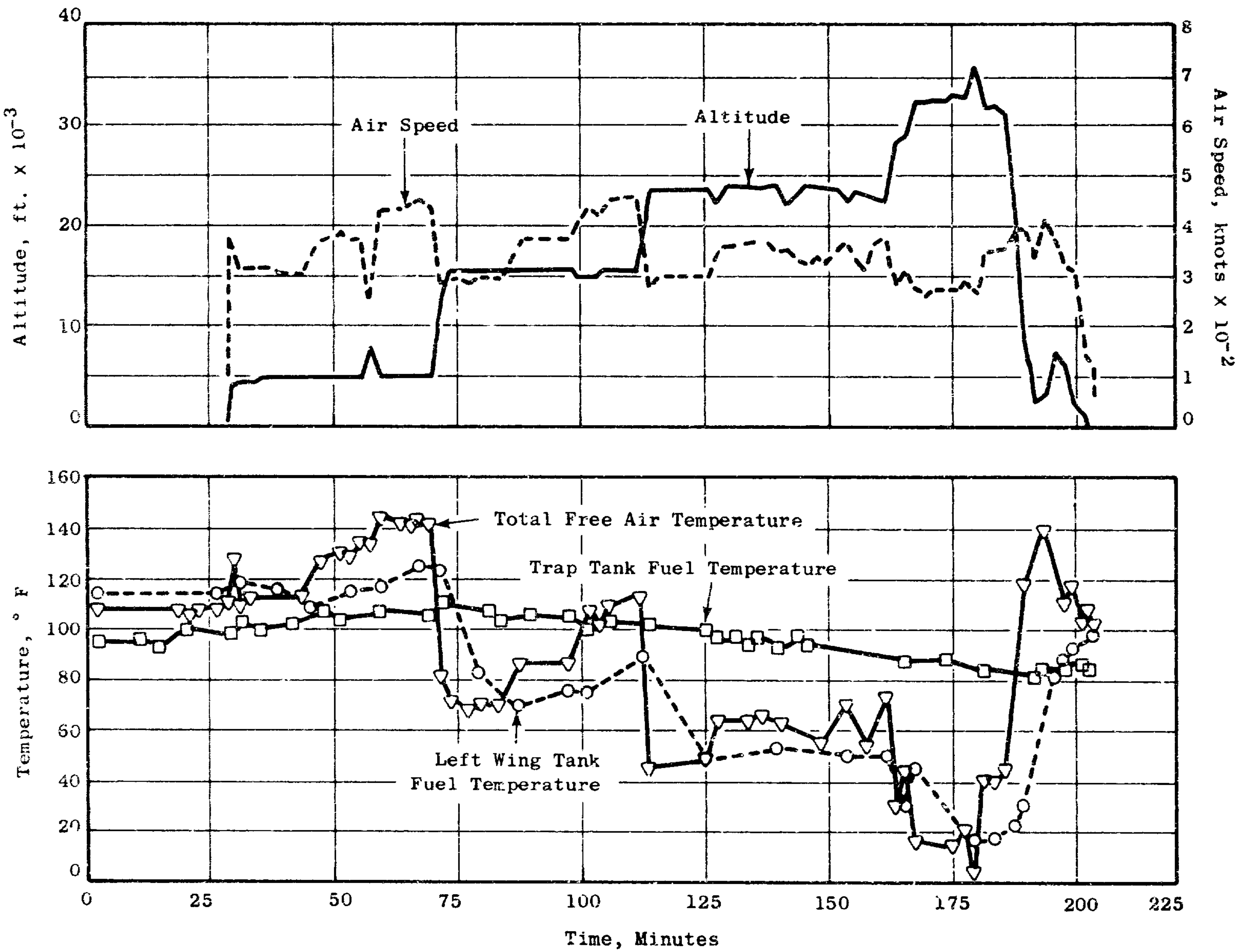


Figure 17. F-111A Fuel Temperatures in Flight.

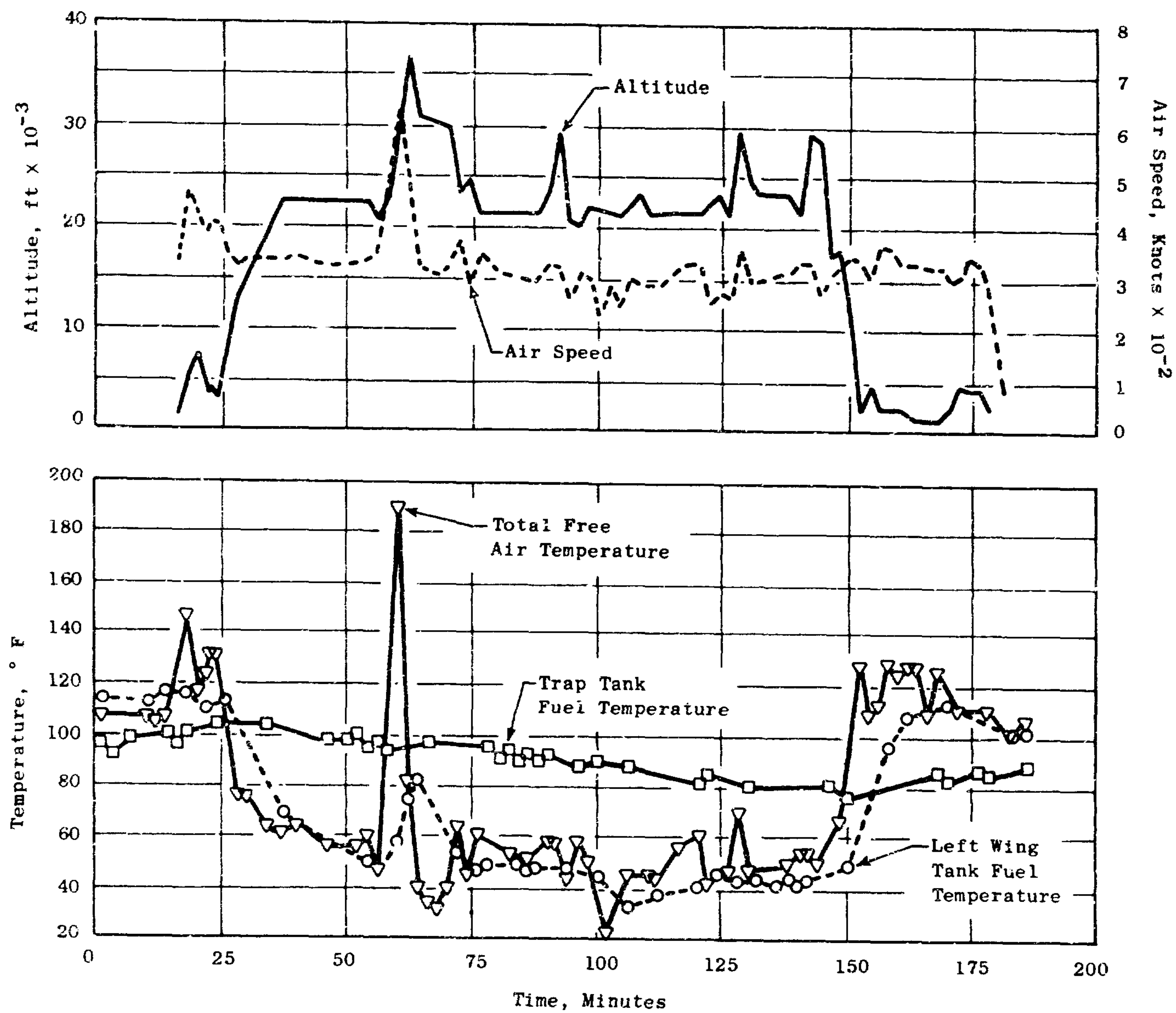


Figure 18. F-111A Fuel Temperatures in Flight.

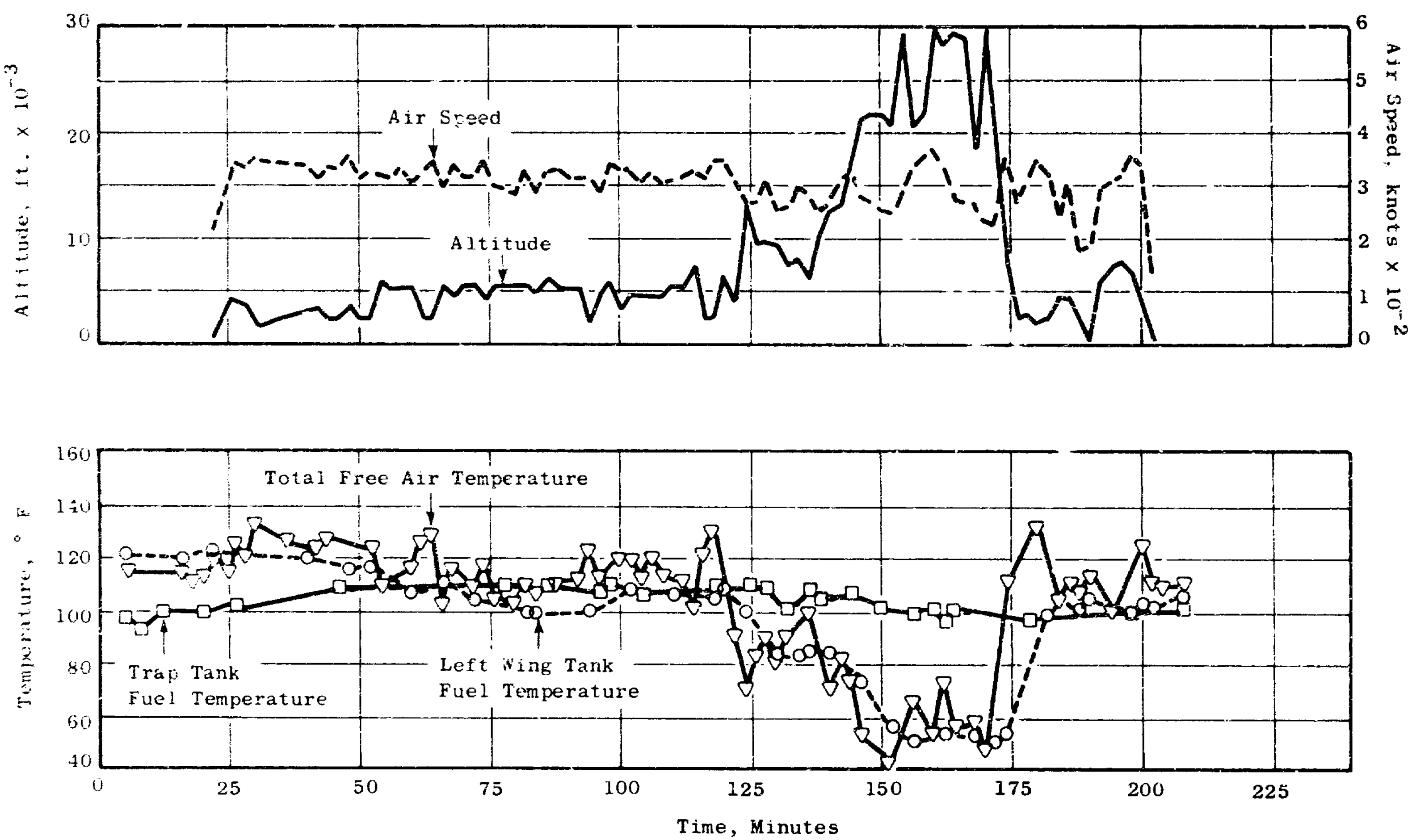


Figure 19. F-111A Fuel Temperatures in Flight.

Figures 20 and 21 show the changes in trap tank and wing tank fuel temperatures over a range of flight altitudes for the F-111A[5] during tests under arctic low temperature conditions at Eielson AFB, Alaska, during the period 1 February to 8 March 1967. Prior to each of the flights the aircraft was cold soaked from 16 to 36 hours.

The overall trap tank fuel temperature cooling rate for Figures 17 through 19 is approximately 0.25° F per minute for an average delta temperature difference of 35° to 40° F between trap tank fuel temperature and total free air temperature. The trap tank fuel temperature heating rates from Figures 17, 18, and 20 appear to be 0.1° to 0.2° F per minute for average delta temperature differences of 25° to 30° F between trap tank fuel temperature and total free air temperature.

Figures 17 through 21 show that the flight profile effects on F-111A wing tank fuel temperatures result in this fuel temperature being essentially equal in magnitude to total free air temperature.

Figures 22 and 23 show the changes in fuselage tank fuel temperatures over a range of flight altitudes and air speeds for the F-5A[4] aircraft during tests under desert high temperature conditions at U.S. Marine Corps Air Station, Yuma, Arizona, during the period 16 July to 14 August 1964. The flight, as shown on Figure 22, was preceded by a hot soak period as shown, where the flights as shown on Figure 23 were preceded by a ground engine run which was preceded by a 2.5-hour hot soak.

Analysis of the fuel temperature data on Figure 22 shows fuselage tank fuel heating rates of 0.2° F per minute, at an average delta temperature difference of 20° F between fuselage tank fuel temperature and total free air temperature, to heating rates approaching 1.0° F per minute for a delta temperature of approximately 65° F.

Figures 24 and 25 show the changes in fuel tank fuel temperatures for the B-52 aircraft under high and low temperature flight conditions.

Figure 24 shows the levels of body and wing tank fuel temperatures for a low altitude flight of the B-52H[7] during a desert high temperature flight at Edwards AFB on 8 August 1961. Figure 25 shows the change in fuel temperature out of the aft body tank for a high altitude flight of the B-52G during tests at Eielson AFB on 5 February 1959.

Figures 26 through 29 show the changes in fuel temperatures for the C-141 and KC-135 aircraft during long duration flight after takeoff at ambient air and fuel temperature levels of 40° and 80° F, respectively.

Figures 26 and 27 are data plots of fuel temperatures into the Nos. 1 and 2 engines for the C-141[2] aircraft on long duration flights from Kadena to Elmendorf and from Elmendorf to Yokota.

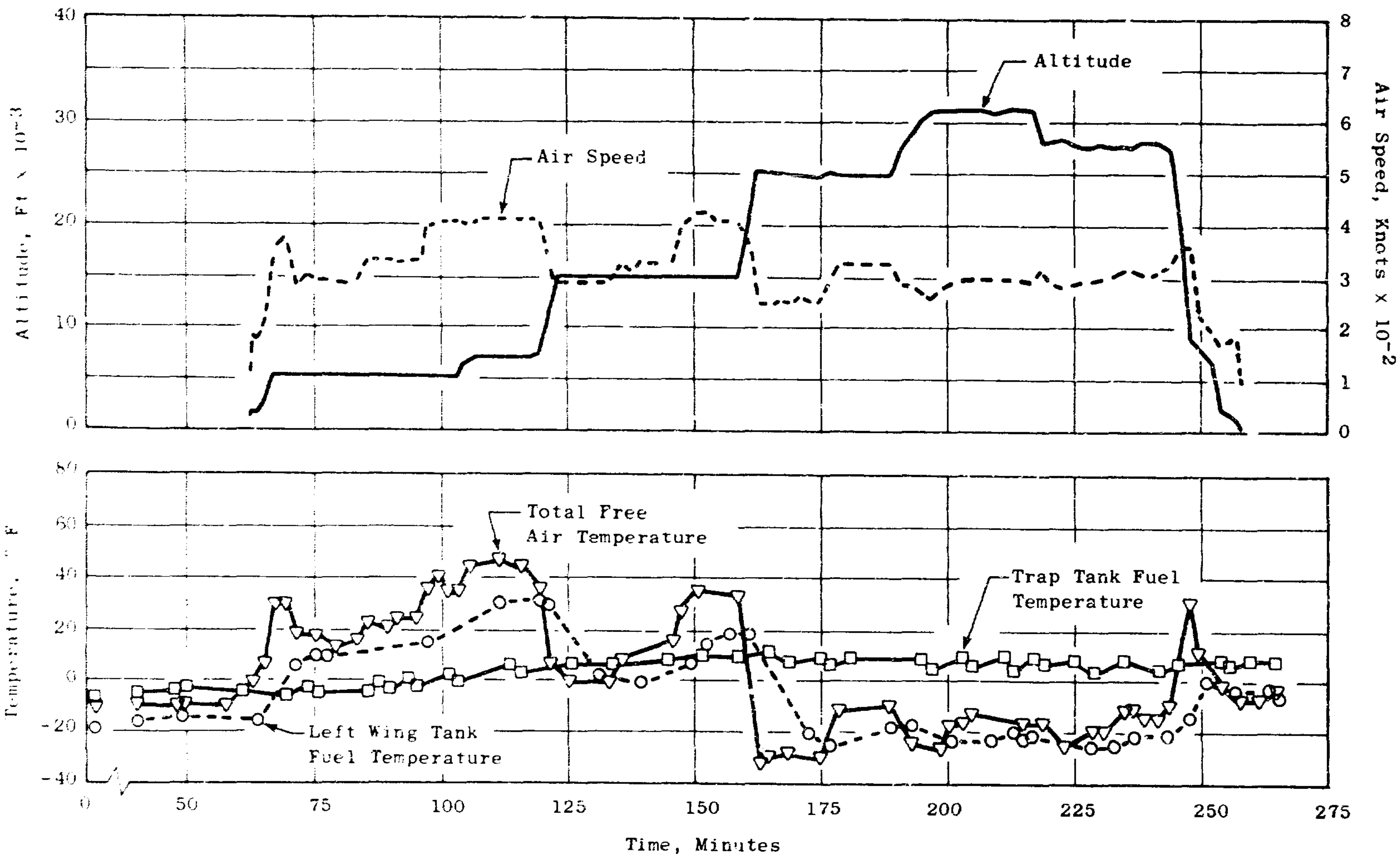


Figure 20. F-111A Fuel Temperatures in Flight.

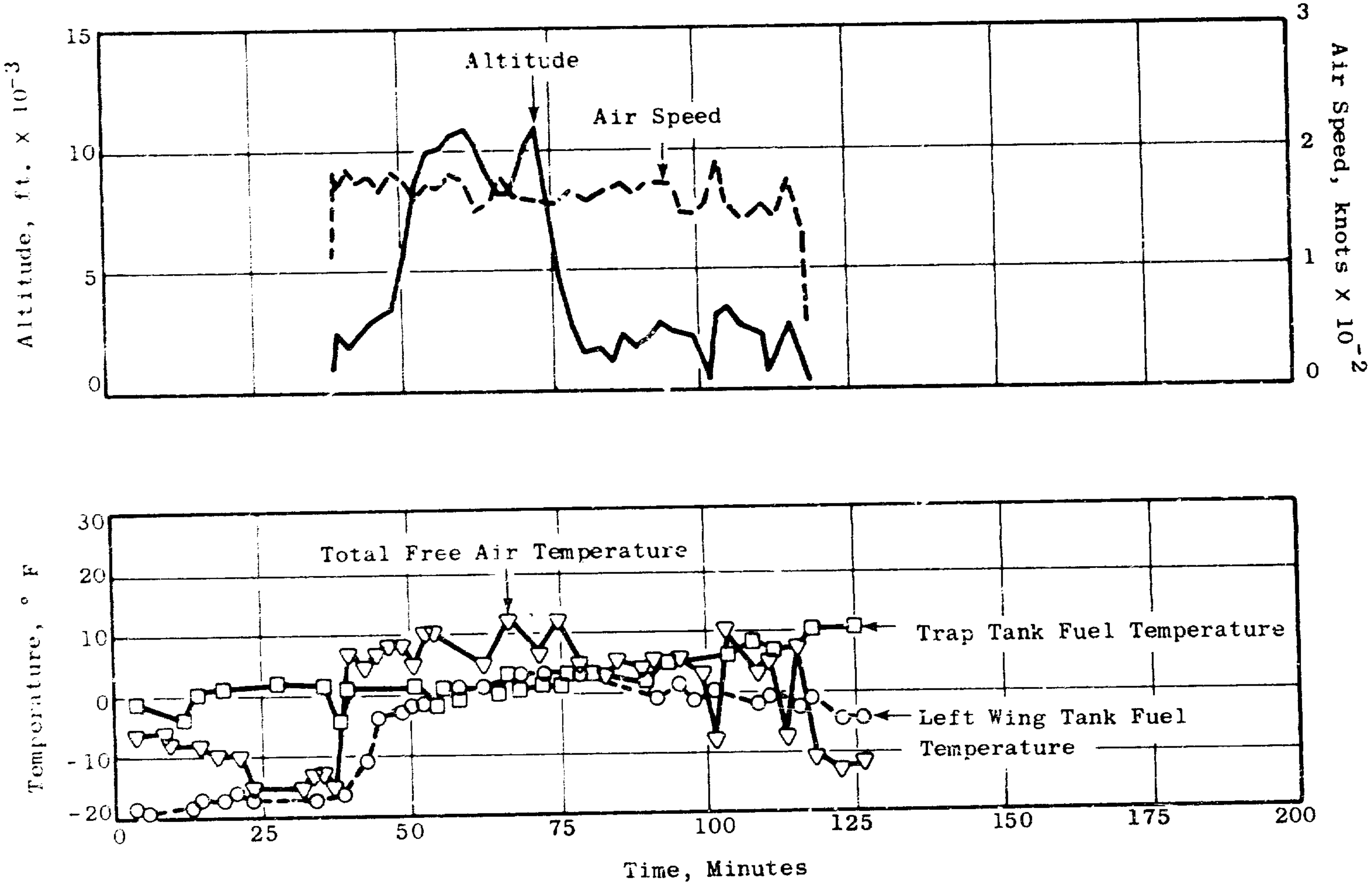


Figure 21. F-111A Fuel Temperatures in Flight.

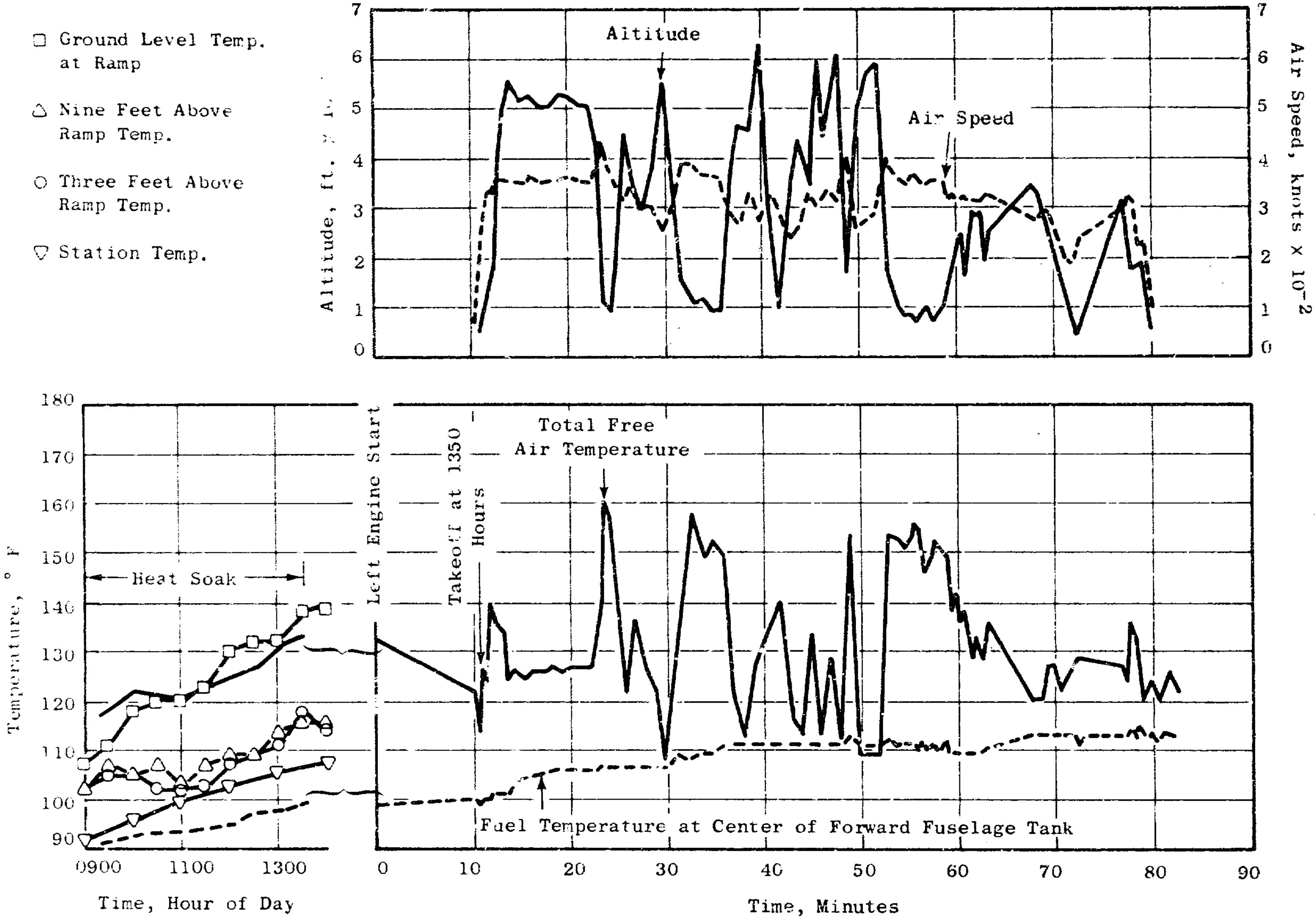


Figure 22. F-5A Fuel Temperatures in Flight.

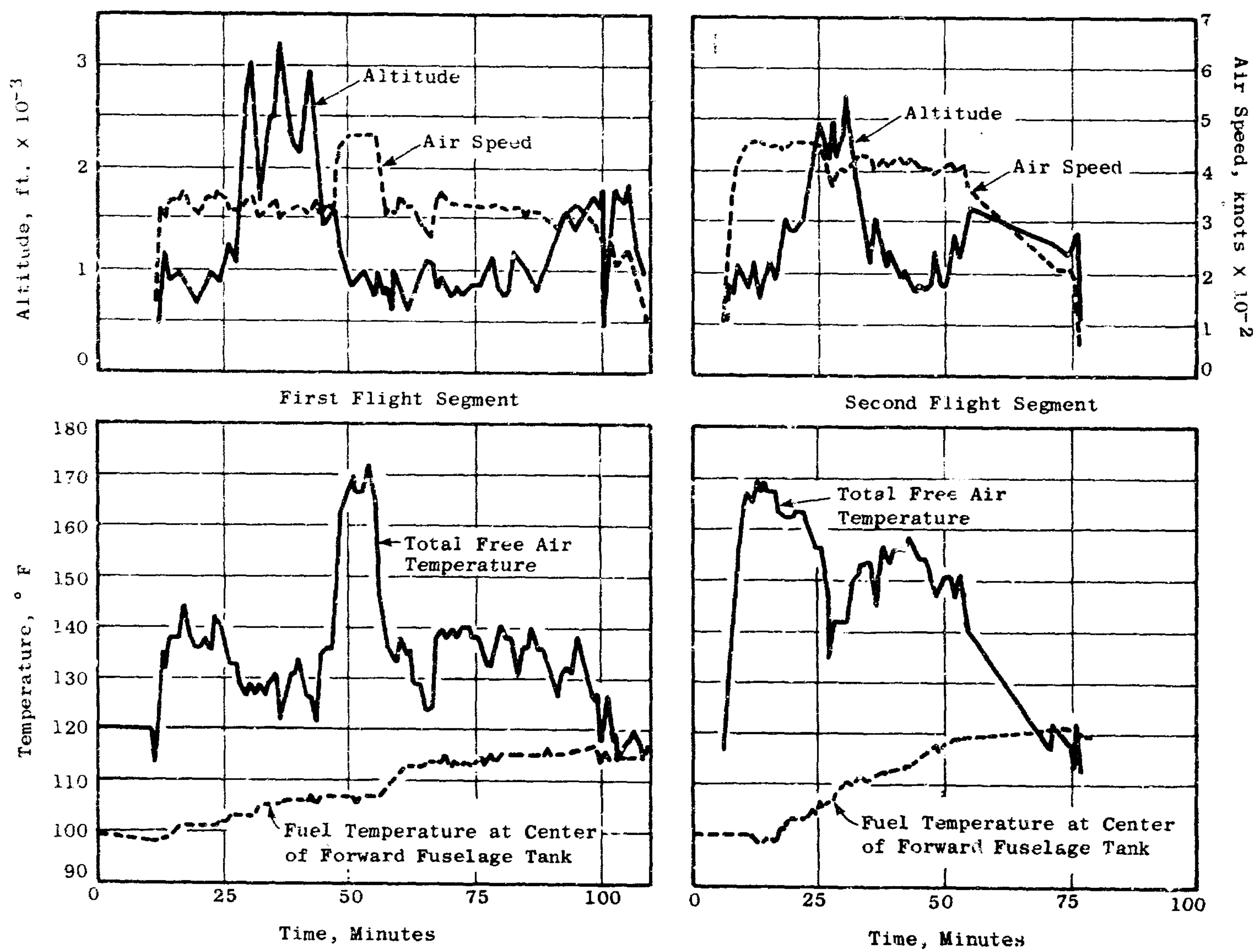


Figure 23. F-5A Fuel Temperatures in Flight.

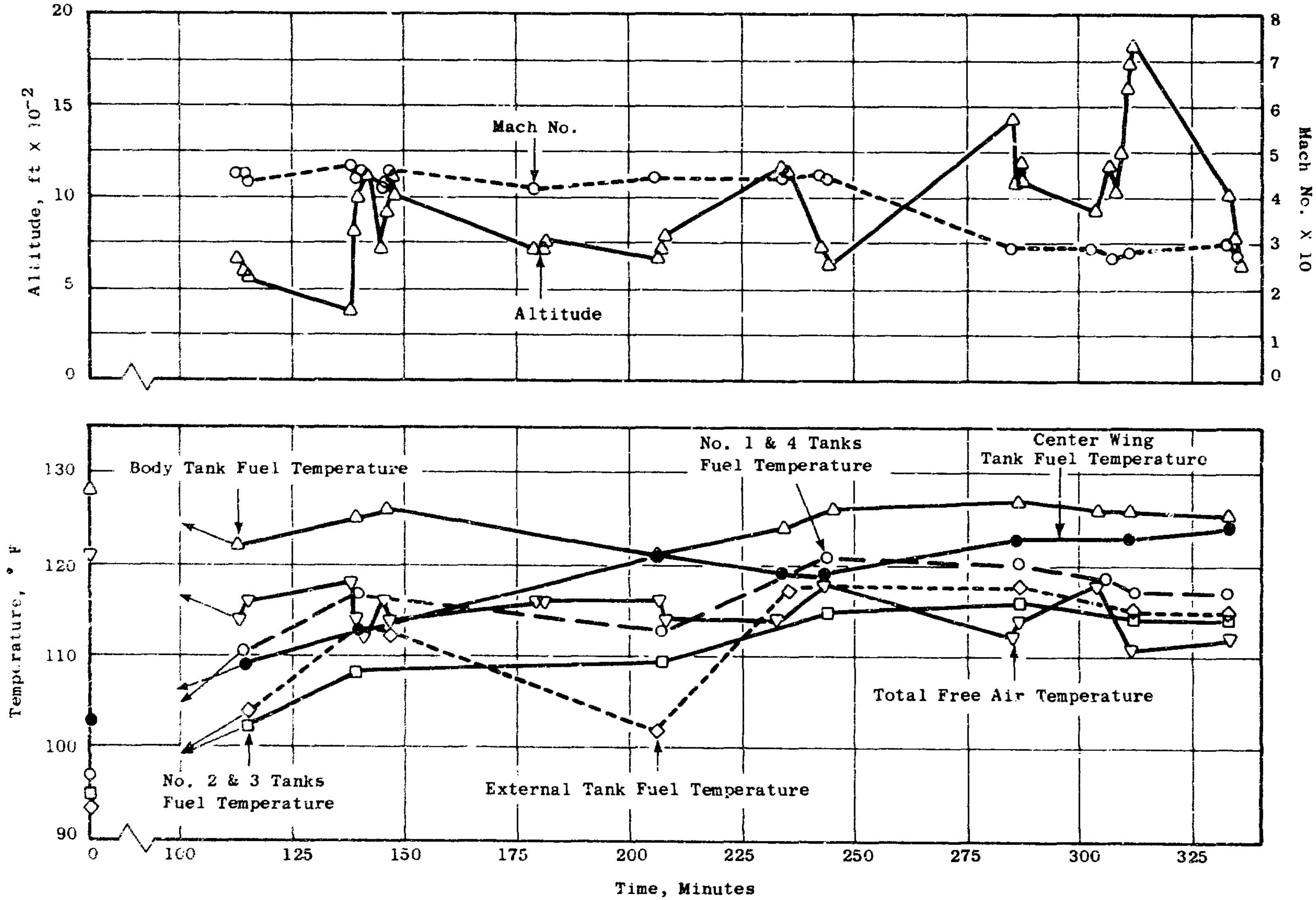


Figure 24. B-52 Fuel Temperatures in Low Level Flight.

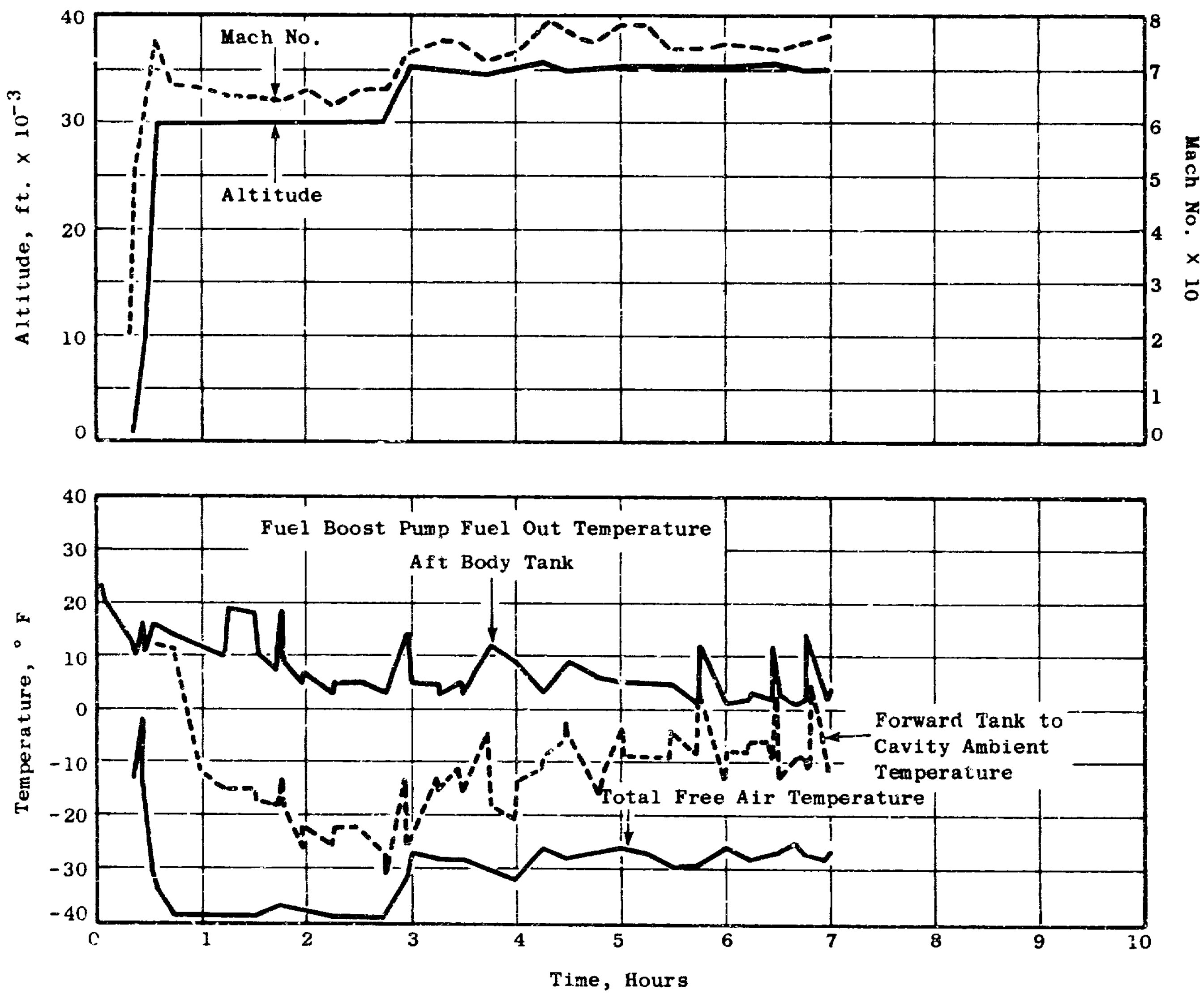


Figure 25. B-52G Fuel Temperatures in Flight.

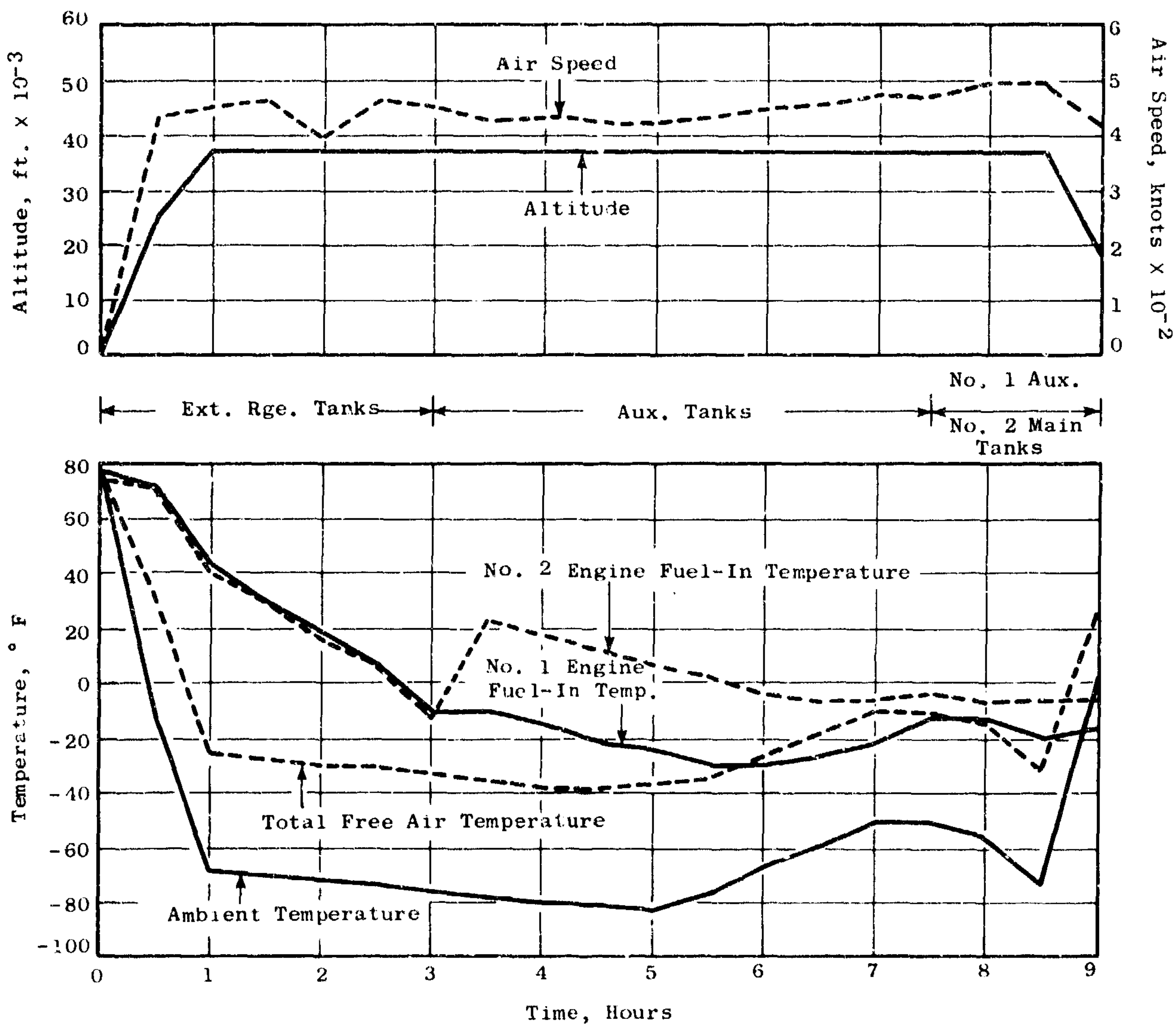


Figure 26. C-141 Fuel Temperatures in Flight.

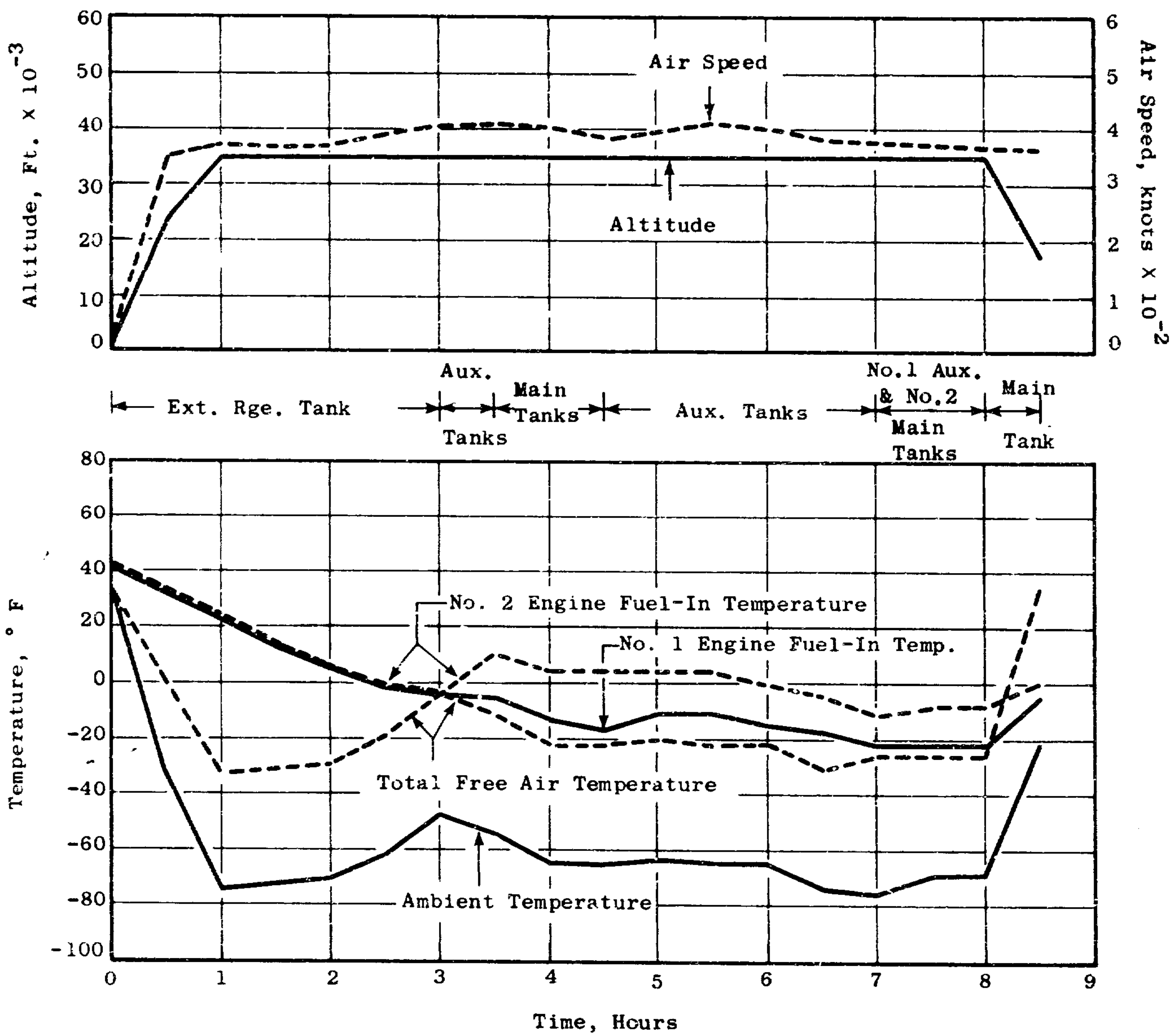


Figure 27. C-141 Fuel Temperatures in Flight.

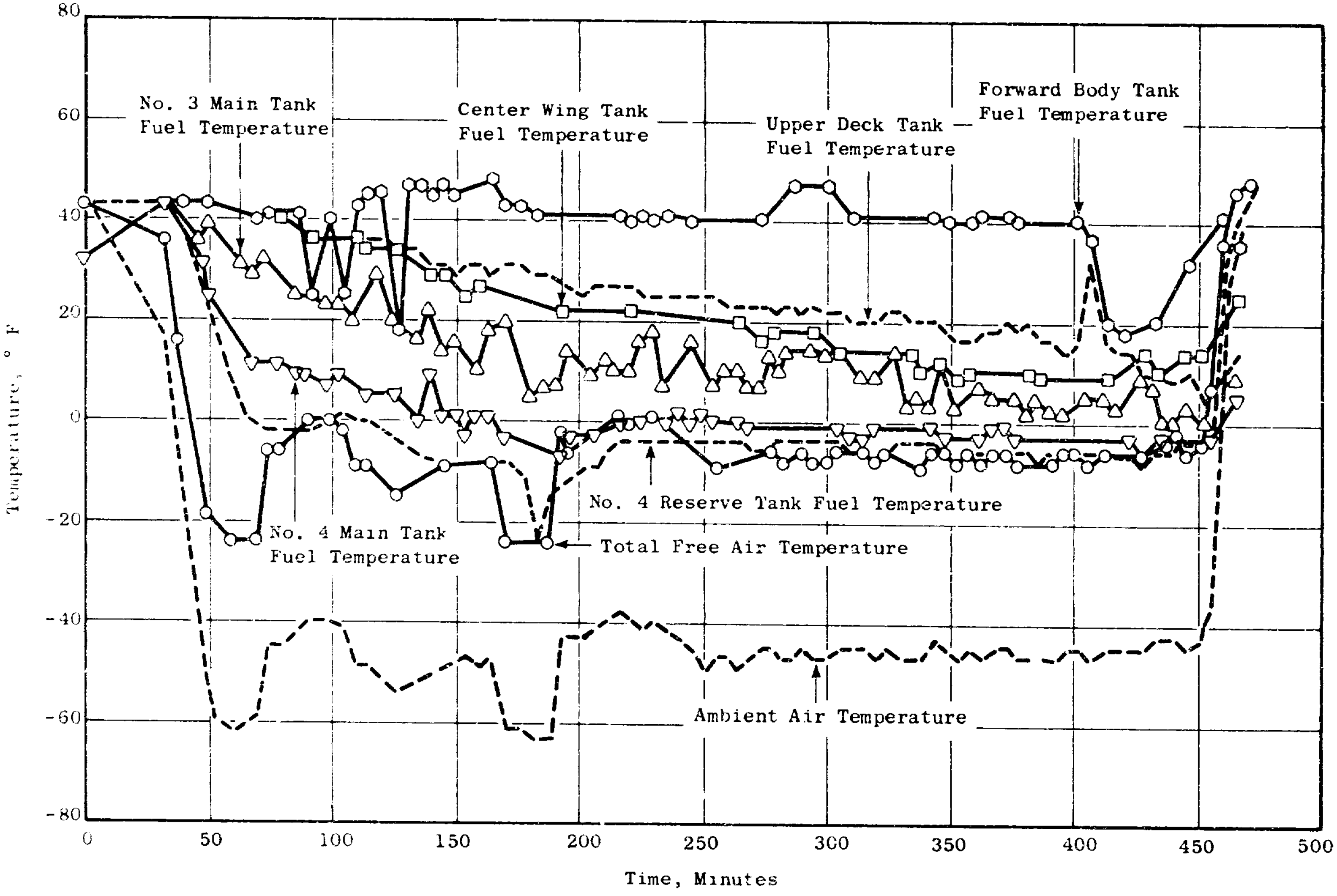


Figure 28. KC-135 Fuel Temperatures in Flight.

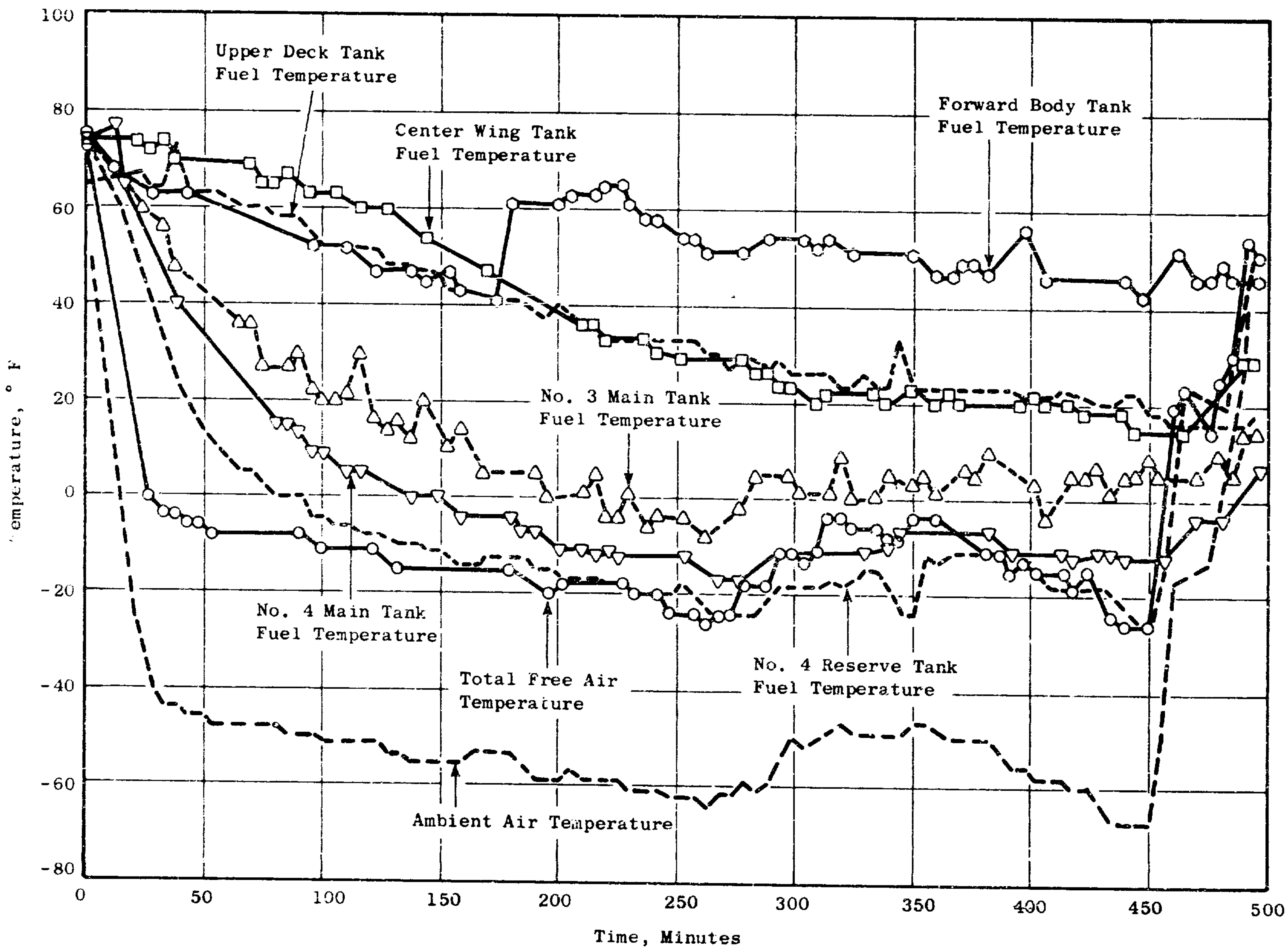


Figure 29. KC-135 Fuel Temperatures in Flight.

The data plots on Figures 28 and 29 for the KC-135[2] aircraft show the results of a specific flight test to determine cooling rates of fuel in the aircraft fuel tank under low temperature conditions. For these flights, the temperatures were recorded prior to takeoff and approximately every 5 minutes during flight. Sufficient fuel was maintained in the tanks to ensure constant immersion of the thermocouples. The thermocouples were located to measure the coldest fuel temperature in a given area. Attempts were made to maintain flight at constant ambient air temperature.

The data plots for the KC-135 flight tests show high initial cooling rates in the number 4 reserve tank and similar trends in the numbers 3 and 4 main tanks. The gradual cooling rates of fuel in body tanks are similar to the trends in fuselage tanks for F-series aircraft.

The data plots thus far have been for operational aircraft in basically subsonic flights with the resulting tank fuel temperatures generally below 120° F. The XB-70A[9] aircraft tank fuel temperatures reached values approaching 165° F during idle descent at the end of sustained Mach 3 cruise. The data plots for a specific flight of the XB-70A are shown in Figure 30. The maximum fuel temperature during idle descent is a result of a portion of the fuel from the aircraft heat exchanger being recirculated to the aircraft fuel tanks.

The calculated flight profile effects on tank fuel temperatures for the B-1 aircraft are shown on Figure 31 for both subsonic and supersonic missions. The data plots show that the flight profile effects are similar to those on present operational aircraft.

The calculated flight profile effects on tank fuel temperatures for an advanced aircraft with a sustained supersonic mission are shown on Figure 32. The abrupt change in fuel temperature in the latter part of the mission is the result of fuel recirculation from the aircraft heat exchangers to the aircraft fuel tanks. This recirculation is required to provide a maximum 250° F fuel inlet temperature to the engine for this flight condition while using the present primary type JP-4 and JP-5 fuels.

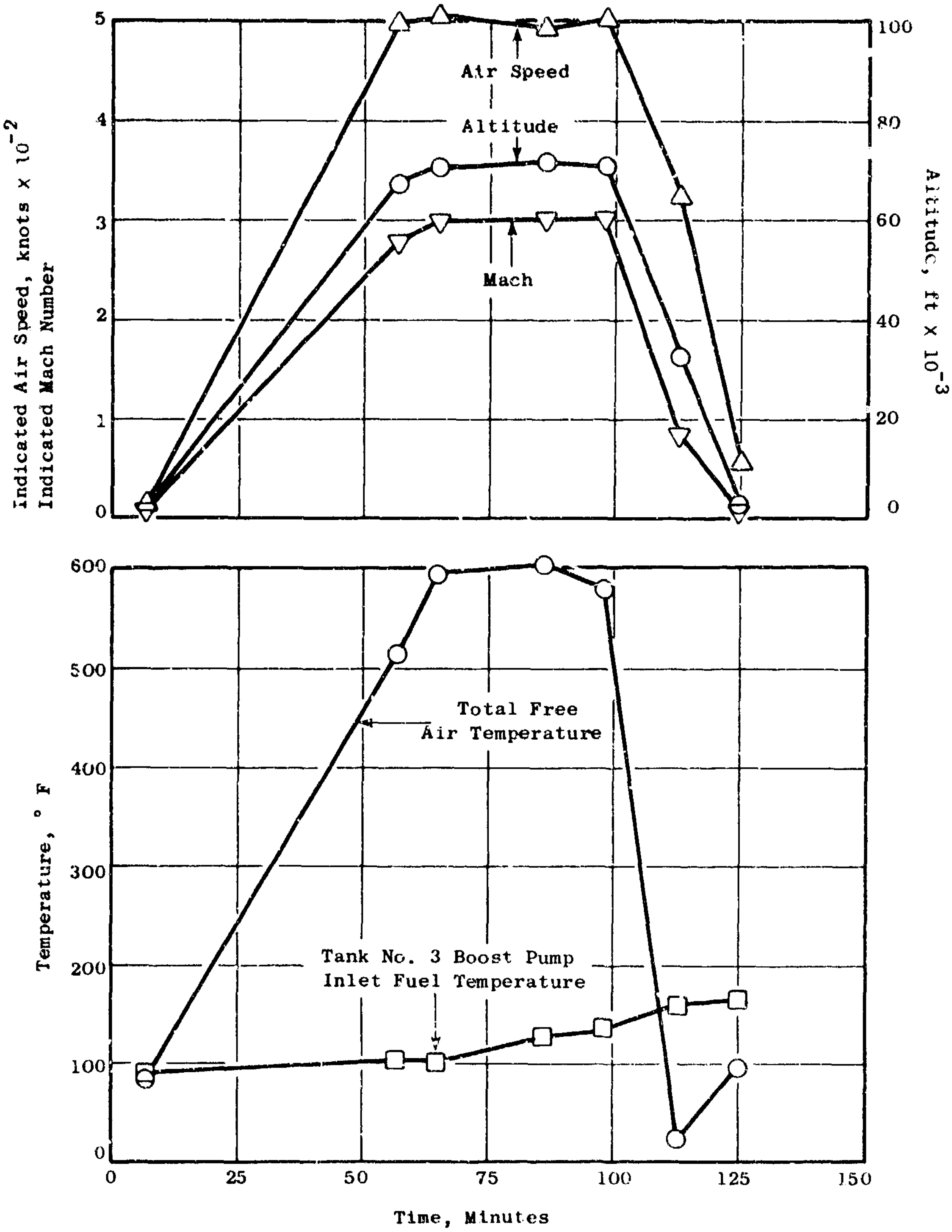


Figure 30. XB-70A Fuel Temperatures in Flight.

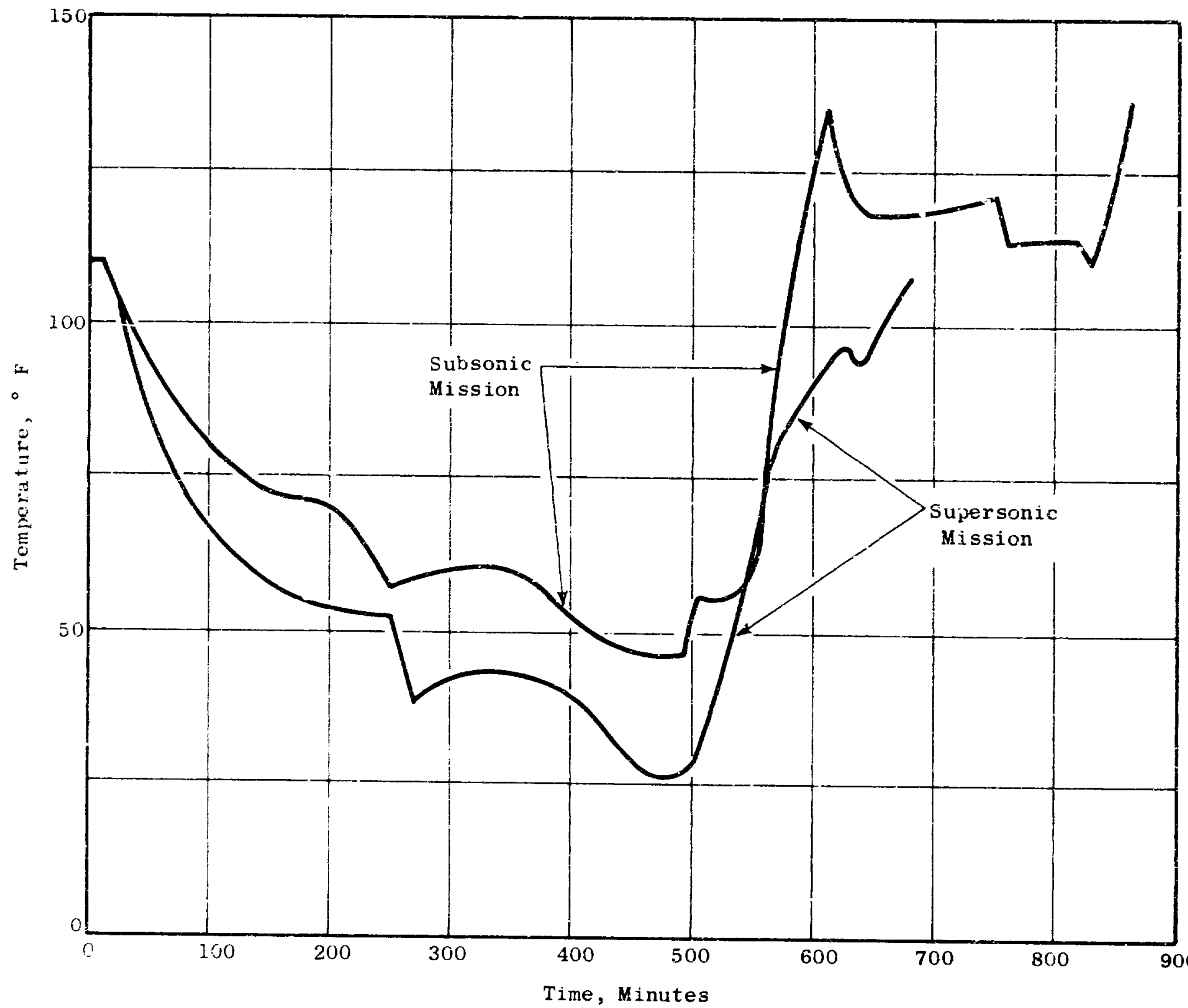


Figure 31. B-1 Fuel Tank Fuel Temperature in Flight.

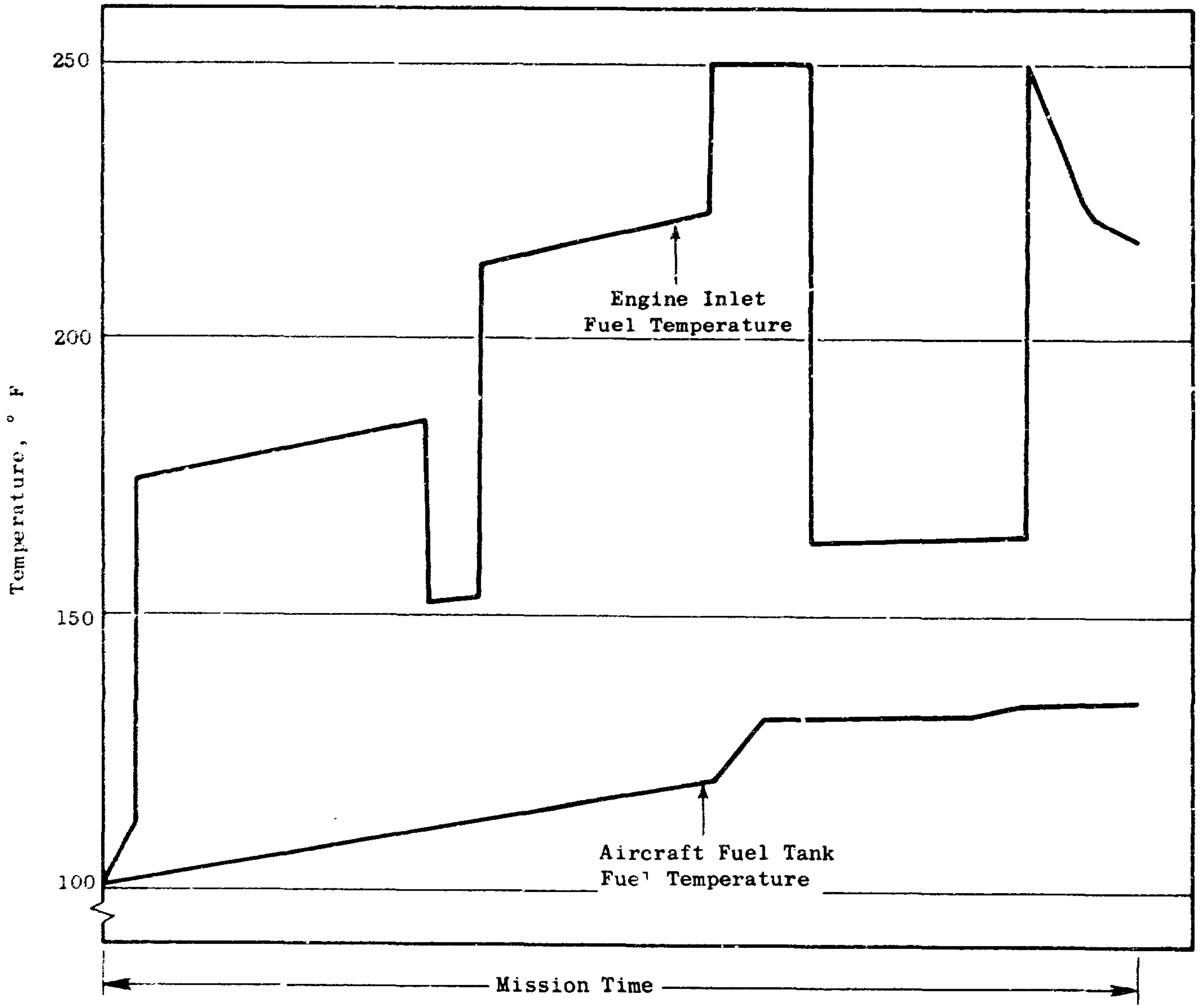


Figure 32. Advanced Aircraft Fuel Tank Fuel Temperature in Flight.

SECTION V

AIRCRAFT AND ENGINE HEAT LOAD INPUT TO FUEL DURING FLIGHT

This section presents information on changes in fuel temperature levels in aircraft and engine fuel systems relating to the major heat loads transferred to the fuel after takeoff and during flight. Included are data plots showing the magnitude and duration of the fuel temperature changes resulting from aircraft boost pumps, electrical, hydraulic, and environmental system heat loads and engine fuel, lube, and hydraulic systems heat loads. Data plots for the F-4C and XB-70A aircraft represent operational type systems, while data plots for the B-1 aircraft are representative of development type systems. Data plots for an advanced sustained supersonic mission aircraft are also presented.

Figures 33 and 34 show the changes in fuel temperatures from the aircraft supply tank to the engine fuel nozzles over a range of flight altitudes for the F-4C[3] during tests under desert high temperature conditions at U.S. Marine Corps Air Station, Yuma, Arizona, during the period 13 July through 16 August 1964. Prior to each of the flights the aircraft was hot soaked for four hours.

Figures 35 and 36 show the changes in fuel temperature from the aircraft supply tank to the engine fuel nozzles over a range of flight altitudes for the F-4C[6] during tests under arctic low temperature conditions at Eielson AFB, Alaska, during the period 5 January through 17 February 1964. Prior to each of the flights, the aircraft was cold soaked for 16 to 60 hours.

For the F-4C aircraft, the major heat loads transferred to the fu... flight are a result of the following components/systems:

- Aircraft fuel system boost pumps
- Aircraft hydraulic system
- Aircraft electrical system
- Engine fuel system
- Engine lubricating system
- Engine hydraulic system

The change in fuel temperature resulting from the aircraft fuel supply boost pumps is shown on Figures 35 and 36 as the difference in fuselage fuel cell fuel temperature and aircraft boost pump manifold fuel temperature. This temperature increase is in the 3° to 5° F range for these flights. For the flights as shown on Figures 33 and 34 the boost pump manifold fuel temperature was recorded 0° to 4° F above fuselage fuel tank fuel temperature. See Table II for the aircraft and engine heat load input to the fuel during flight.

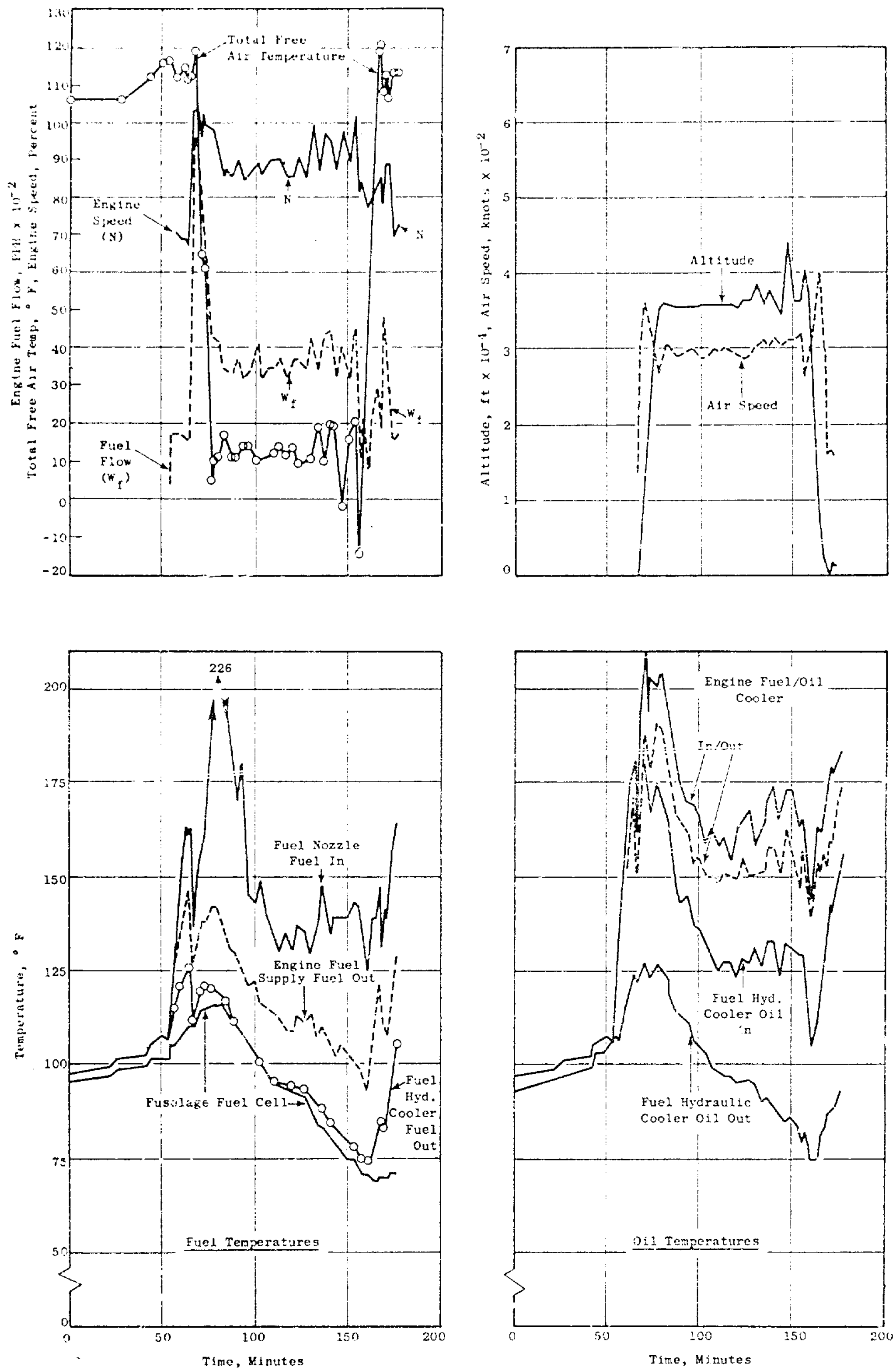


Figure 33. F-4C Inflight Fuel Heat Loads.

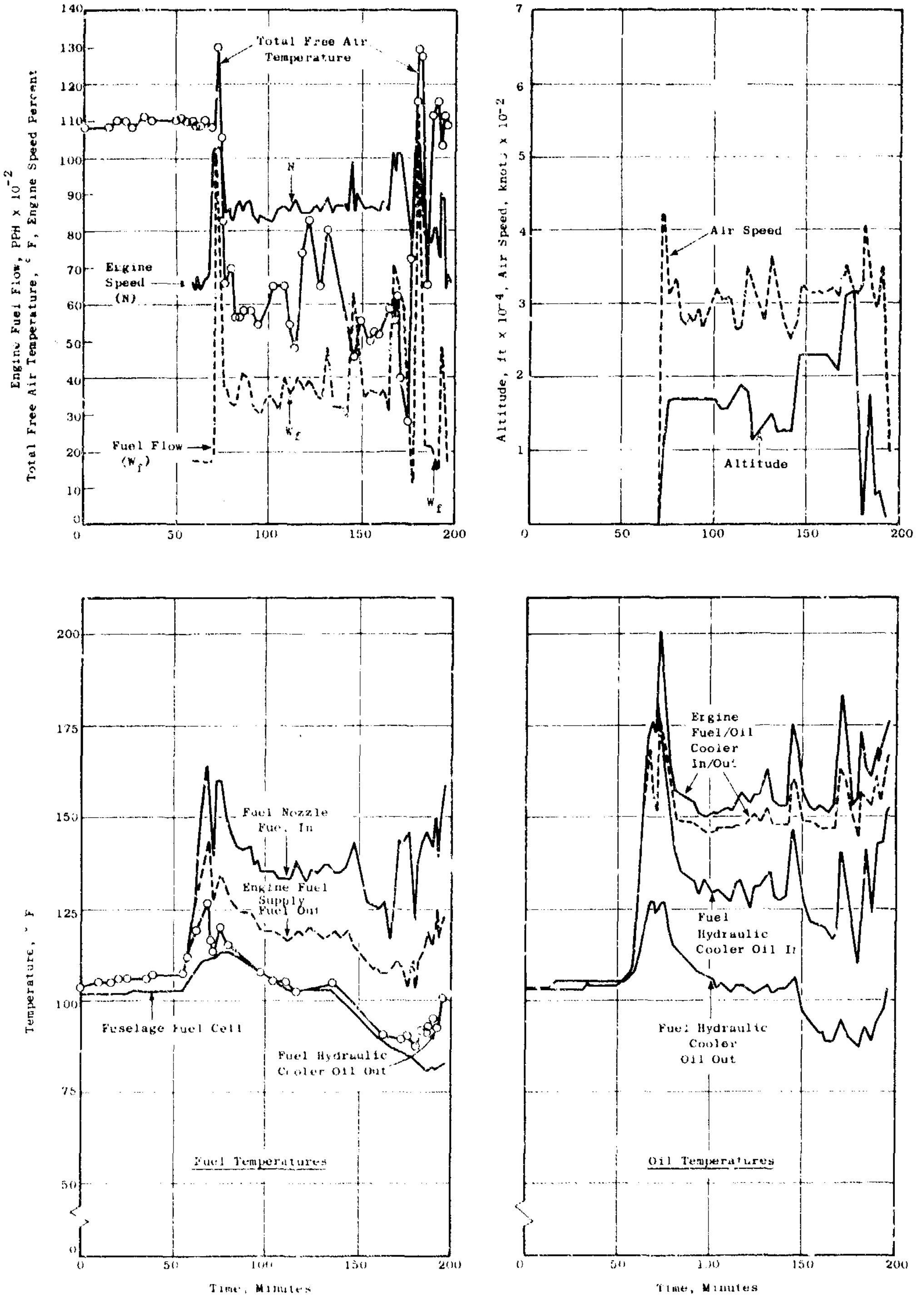


Figure 34. F-4C Inflight Fuel Heat Loads.

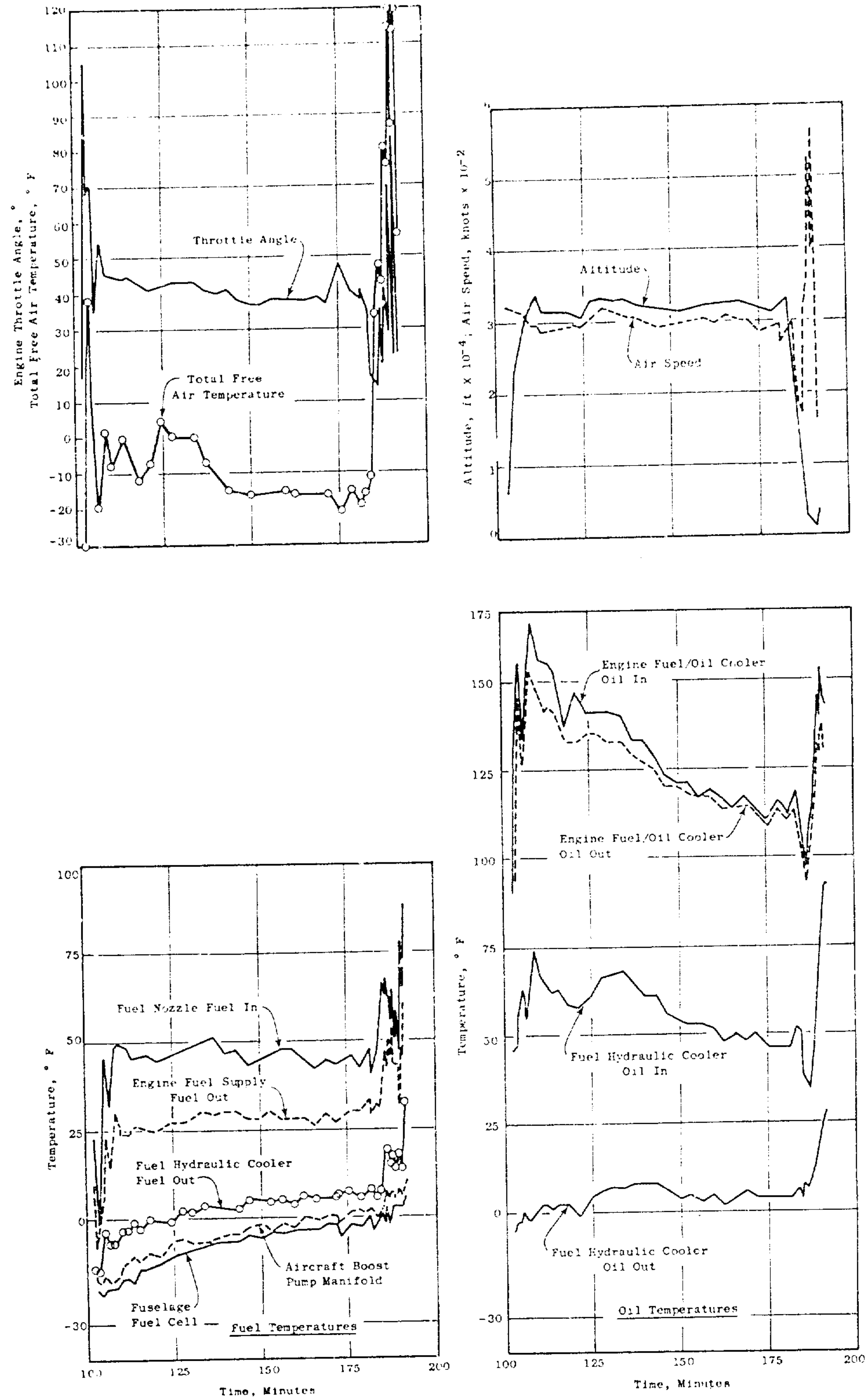


Figure 35. F-4C Inflight Fuel Heat Loads.

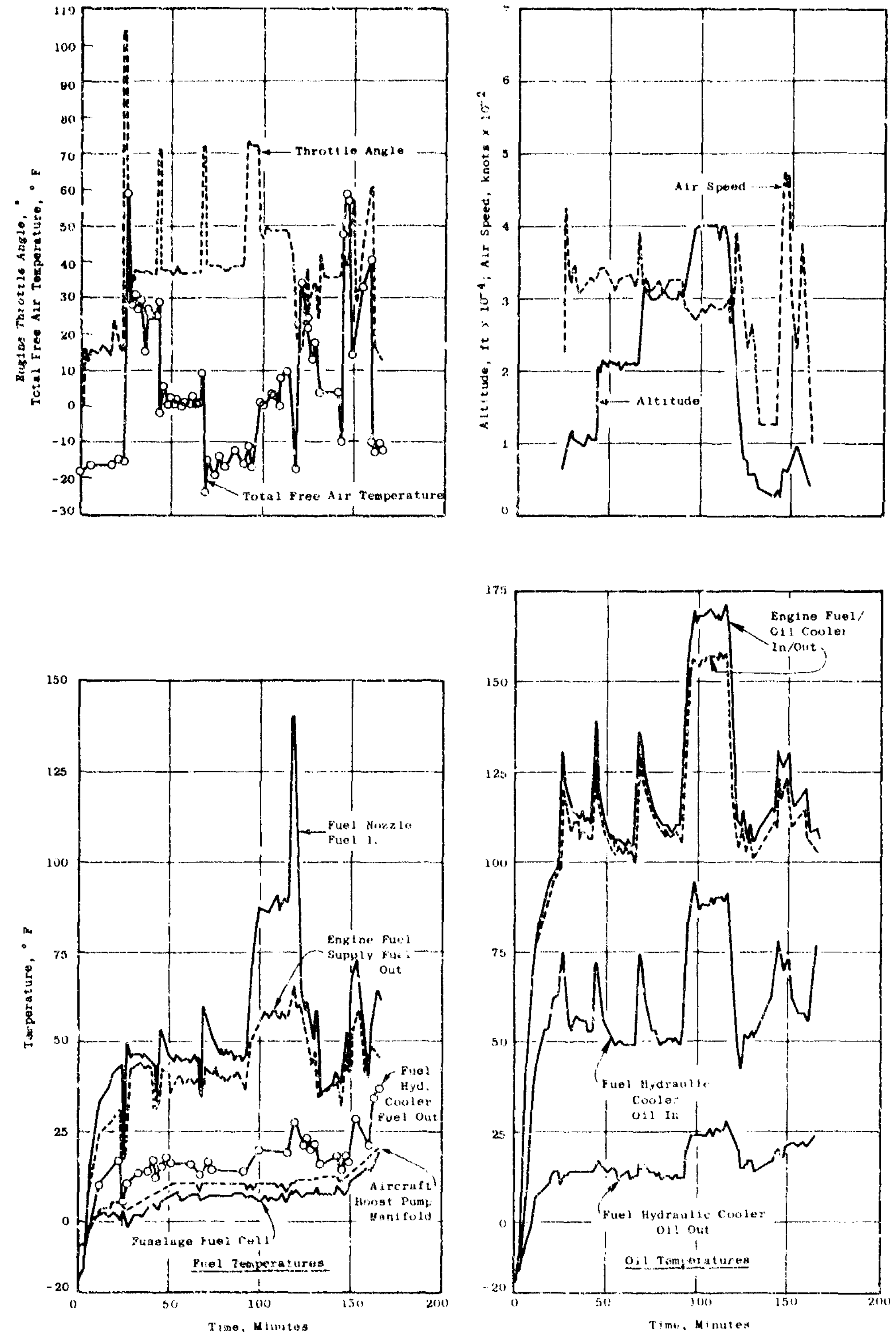


Figure 36. F-4C Inflight Fuel Heat Loads.

Table II. Aircraft and Engine Heat Load Input to Fuel During Flight, ° F.

System	F-4* Aircraft	B-1** Aircraft	Advanced** Supersonic Aircraft	XB-70 Aircraft
Aircraft Fuel System Boost Pump	3-5		1-1.5	
Aircraft Hydraulic System	4-12	25-30***	32-46	68-84***
Aircraft Electrical System	25-30		5-7	
Engine Fuel System	15-24	75	55-59	
Engine Lube System	20-25	106	26-31	65-70****
Engine Hydraulic System	3-4	20	3	

* Subsonic cruise
** Supersonic cruise
*** Includes aircraft boost pump, electrical system, hydraulic system, and environmental system heat load inputs.
**** Includes fuel temperature rise in main fuel system from engine inlet to combustor.

The aircraft hydraulic system heat loads for the F-4, from information received from McDonnell Douglas, are as follows:

Aircraft Flight Condition	Heat Rejection, Btu/Min/Engine		
	Hot Day	Standard Day	Cold Day
Taxi and Takeoff	145	130	90
Acceleration and Climb	145	130	90
Cruise and Endurance	100	100	100
High Speed	300	300	300
Idle Descent	50	50	50
Landing	170	145	85

The changes in fuel temperatures resulting from the aircraft hydraulic system are shown in Figures 33 through 36 as the difference between aircraft tank or boost pump manifold temperature and fuel/hydraulic cooler fuel-out temperature. The fuel/hydraulic cooler oil-in and oil-out temperatures are also shown on these figures.

The aircraft electrical system for the F-4C is driven by a constant-speed drive (CSD). The CSD oil is supplied directly from the engine oil tank and is returned downstream of the engine fuel/oil coolers directly to the tank, resulting in an oil tank oil temperature increase. For the flights as shown on Figures 33 to 36, the CSD return oil was generally 25° to 30° F hotter than the oil-out of the engine fuel/oil coolers. The CSD heat rejection to the engine lube oil is generally in the range of 400 to 600 Btu/min.

The engine fuel system for the F-4C aircraft is a bypassing-type system with a constant displacement gear pump supplying fuel flow in excess of that required for engine operation. The excess fuel flow is returned (i.e., bypassed) to the inlet of the constant displacement gear pump. For Figures 33 through 36, the fuel temperature rise resulting from the engine fuel supply system is shown as the difference between the fuel/hydraulic cooler fuel-out temperature and the engine fuel supply fuel-out temperature. The spikes in the temperature levels are a result of reduction in engine speed requirements and throttle chops to idle.

The F-4C engine heat rejection to the engine lube oil depends upon engine power level and flight conditions. The engine heat rejection for a low altitude (10,000-foot) flight varies from approximately 600 Btu/min at Mach 0.4, to 1000 Btu/min at Mach 0.8, and to 2600 Btu/min at Mach 1.3. For a medium altitude (35,000-foot) flight, the heat rejection varies from approximately 800 Btu/min at Mach 0.6, to 1000 Btu/min at Mach 1.2, and to 2500 Btu/min at Mach 2.0. For a high altitude (55,000-foot) flight, the heat rejection varies from approximately 900 Btu/min at Mach 1.0, to 1900 Btu/min at 2.0, and to 2800 Btu/min at Mach 2.4.

For the F-4C the engine heat load is rejected to the engine fuel/oil coolers and to the aircraft air/oil cooler. The CSD and the engine hydraulic system heat loads are also rejected to these same coolers.

The F-4C aircraft air/oil cooler is located in the engine scavenge oil return system, upstream of the engine fuel/oil cooler. At low Mach number flight conditions, the aircraft air/oil cooler can dissipate up to 900 Btu/min; but, this steadily decreases to zero and adds heat load to the engine oil as the aircraft approaches Mach 2 and above, where the engine inlet air temperature can be as much as 150° F above the combined engine scavenge oil temperature.

For Figures 33 through 36, the fuel temperature changes (for the resulting combined engine, CSD, and engine hydraulic system heat loads rejected to the engine fuel/oil coolers) are shown as the difference between the engine fuel supply fuel-out temperature and the fuel nozzle fuel-in fuel temperature. The engine cooler oil-in and oil-out temperatures also are shown on these figures.

The engine hydraulic system cooling flow is returned to the rear gearbox, and the heat load is rejected to the engine lube oil. The heat load is not sensitive to aircraft Mach number and altitude, and varies from approximately 20 Btu/min at idle engine speed to 185 Btu/min at maximum engine speed.

The XB-70A aircraft represents fuel systems designed to operate at sustained supersonic speeds and to utilize aircraft fuel as a major heat sink. The aircraft fuel heat sink coolant loop, parallel to the engine supply system, includes heat exchangers for cooling the landing gear and drag chute, each of four hydraulic systems, and six accessory drive systems. The aircraft coolant loop fuel flow is mixed with additional flow from the parallel engine supply line to provide the engine demand. If engine demand is less than aircraft coolant loop flow, the excess coolant loop flow is returned to the sump tank.

Figure 37 shows the changes in measured and calculated fuel temperatures in the XB-70A aircraft and engine fuel systems resulting from a flight which consisted of 32 minutes at or near Mach 3.0 cruise. The aircraft heat load rejected to the fuel is represented by the difference between the tank No. 3 boost pump inlet temperature and the aircraft water boiler fuel-out temperature. Aircraft total fuel coolant loop heat rejection is also shown on Figure 37. For most of the flight, the aircraft coolant loop fuel flow is mixed with additional fuel flow from the engine supply line, resulting in a calculated engine inlet fuel temperature as shown on Figure 37.

Main engine system fuel pumping, main engine fuel/oil and fuel hydraulic heat exchanger, and environmental heating heat load inputs to the main engine fuel flow are represented by the difference between calculated engine inlet fuel temperature and No. 3 engine main nozzle fuel-in temperature.

Afterburner system fuel pumping, afterburner fuel/oil exchanger, and environmental heating heat load inputs to the afterburner fuel flow are represented by the difference between the calculated engine inlet fuel temperature and the No. 3 engine A/B metering-valve-out fuel temperature.

At the end of supersonic cruise, during the latter portion of the descent phase, the aircraft coolant loop supplies the total fuel flow to the engines and returns excess coolant flow to the sump fuel tank, resulting in a continuing increase in aircraft tank fuel temperature.

The B-1 aircraft represents fuel systems design for present development type aircraft which utilize aircraft fuel as a major heat sink. The major heat loads transferred to the engine fuel during flight are a result of aircraft boost pump, electrical, hydraulic, and environmental system heat loads and engine fuel pumping, engine lube system heat rejection, and engine hydraulic system heat loads.

Figures 38 and 39 are data plots showing the calculated main fuel tank fuel temperatures, the calculated aircraft heat load input to the engine fuel, and the fuel temperature rise resulting from the aircraft heat loads for the subsonic and supersonic design missions.

For the B-1/F101 main engine fuel system, a vane pump provides high pressure fuel flow controlled by a bypassing-type main fuel control. ' main engine heat exchanger provides the heat sink for the engine lube oil during nonafterburning operation and a portion of the heat sink during afterburning operation. A schematic of the F101 engine fuel system is shown on Figure 40.

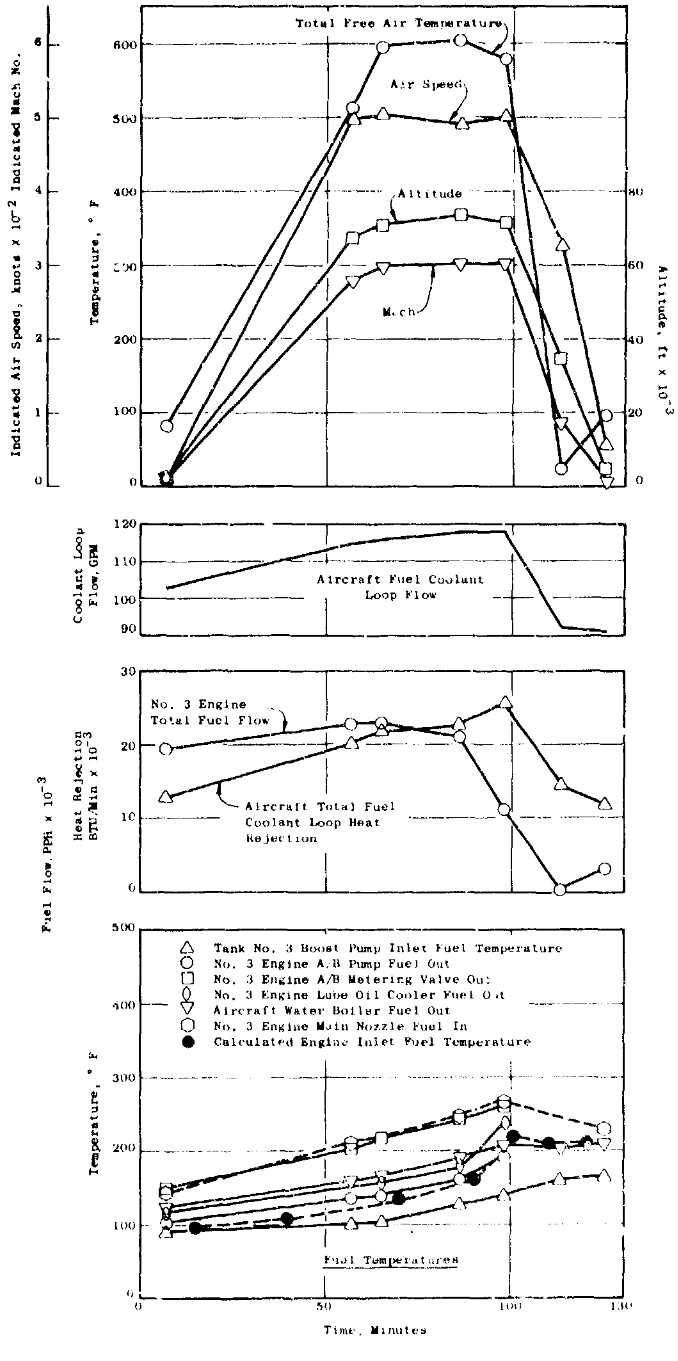


Figure 37. XB-70 Inflight Fuel Heat Loads.

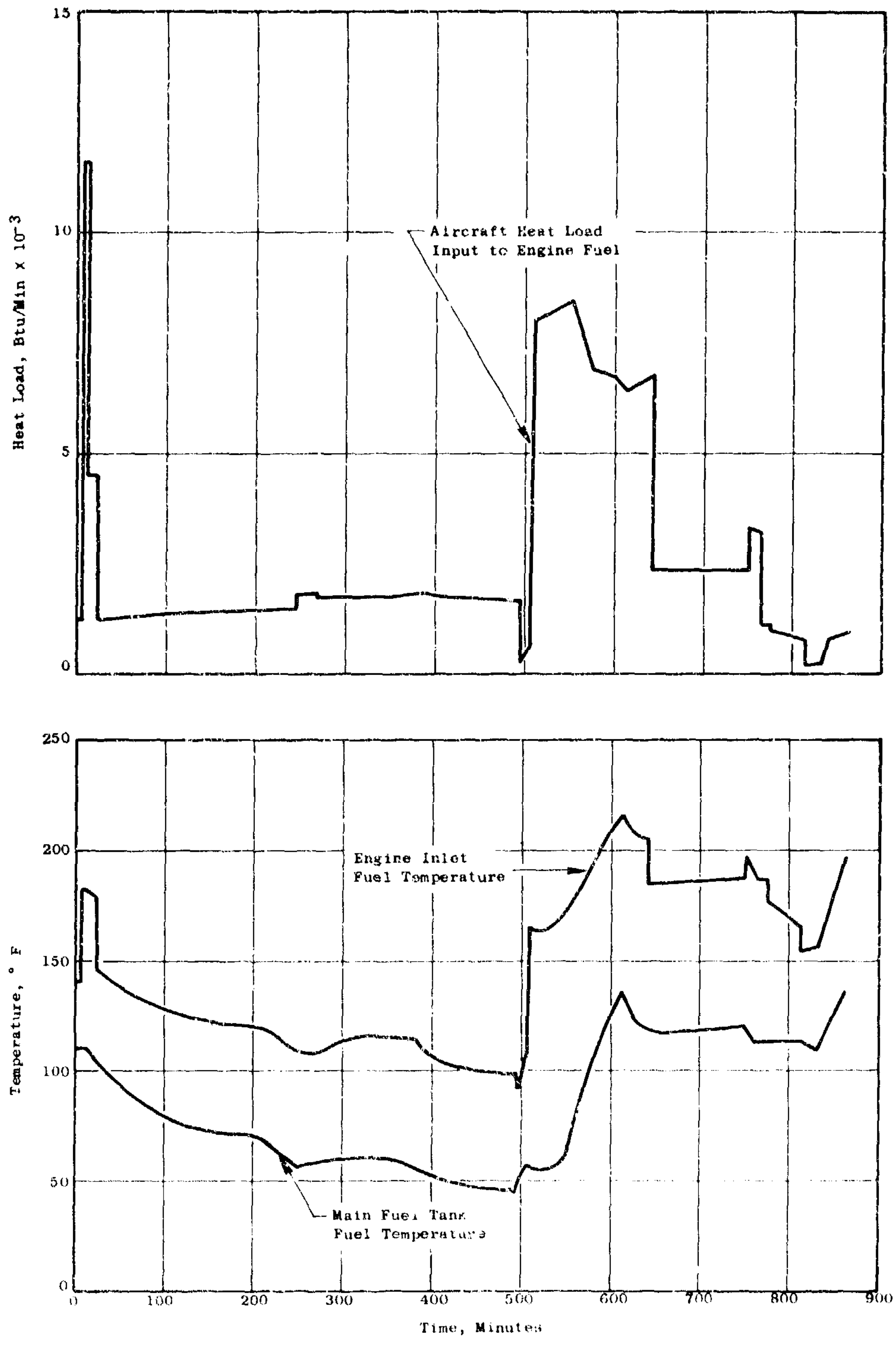


Figure 38. B-1 Aircraft Heat Load Inputs to Engine Fuel and Fuel Temperature Changes During Subsonic Mission.

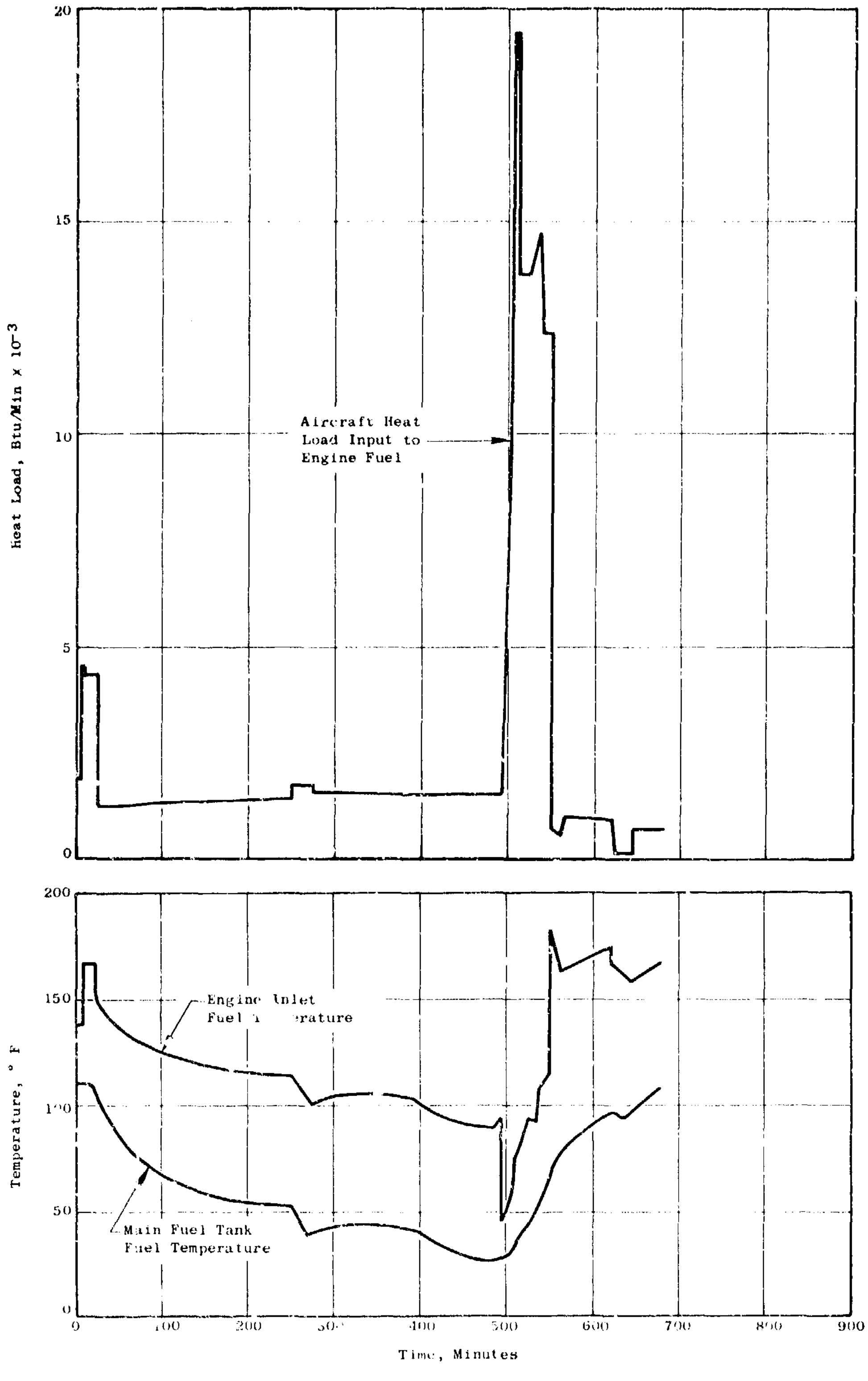


Figure 39. B-1 Aircraft Heat Load Inputs to Engine Fuel and Fuel Temperature Changes During Supersonic Mission.

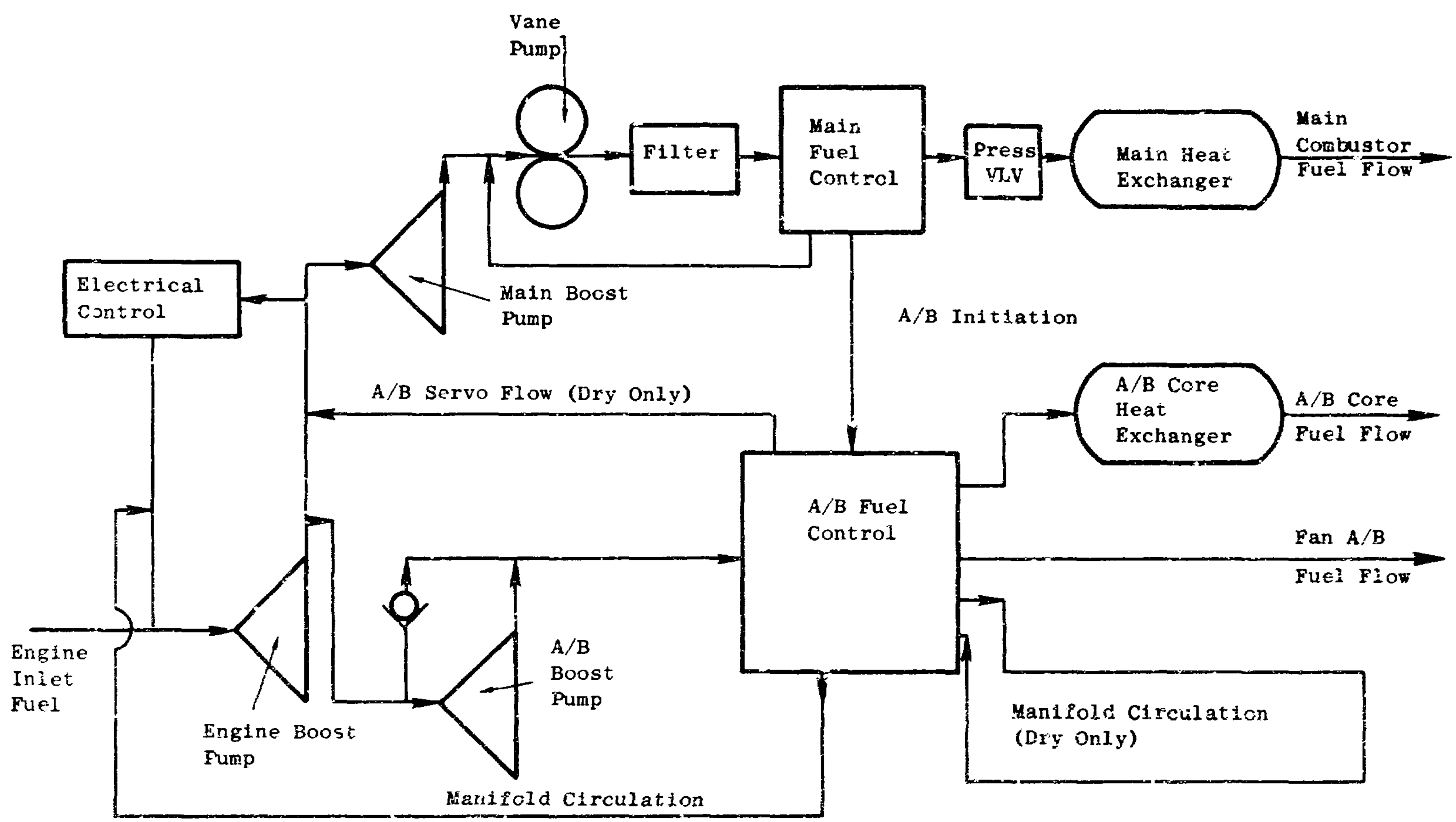


Figure 40. Schematic B-1/F101 Engine Fuel System.

During afterburner operation a shuttered centrifugal pump provides high pressure fuel flow to a metering-type afterburner fuel control. A heat exchanger located in the core afterburner fuel line provides additional heat sink for the engine lube oil during afterburner operation.

Figure 41 shows the F101 calculated engine heat loads transferred to the engine fuel during the subsonic mission and the resulting main engine fuel temperature changes. The continuous plots as shown on Figure 41 are for the heat loads and resulting fuel temperature changes in the fuel flow to the main engine combustor. However, during periods of afterburner operation, the afterburner fuel flow has a heat load input to the afterburner fuel from pumping heat loads. Also, the afterburner fuel flow provides additional heat sink for the engine lube oil in the afterburner heat exchanger.

During afterburner operation. the afterburner fuel system has the following effects on engine fuel flow:

AFTERBURNING OPERATING POINT
(Shown on Figures 41)

Heat Load/Fuel Temperature*	(1)	(2)
A	699	474
B	1565	1705
C	182	195
D	187	206
E	199	220

*A Average Heat load input to afterburner fuel flow from afterburner fuel pumping and metering in Btu/min.

B Average heat sink provided by afterburner heat exchanger, for engine lube oil, during afterburner operation in Btu/min.

C Average fuel inlet temperature to afterburner fuel pump during afterburner operation in ° F.

D Average fuel inlet temperature to afterburner heat exchanger during afterburner operation in ° F.

E Average fuel temperature at exit of afterburner heat exchanger during afterburner operation in ° F.

Also shown on Figure 41 is the exhaust nozzle fluid power system heat load input to the engine lubricating oil.

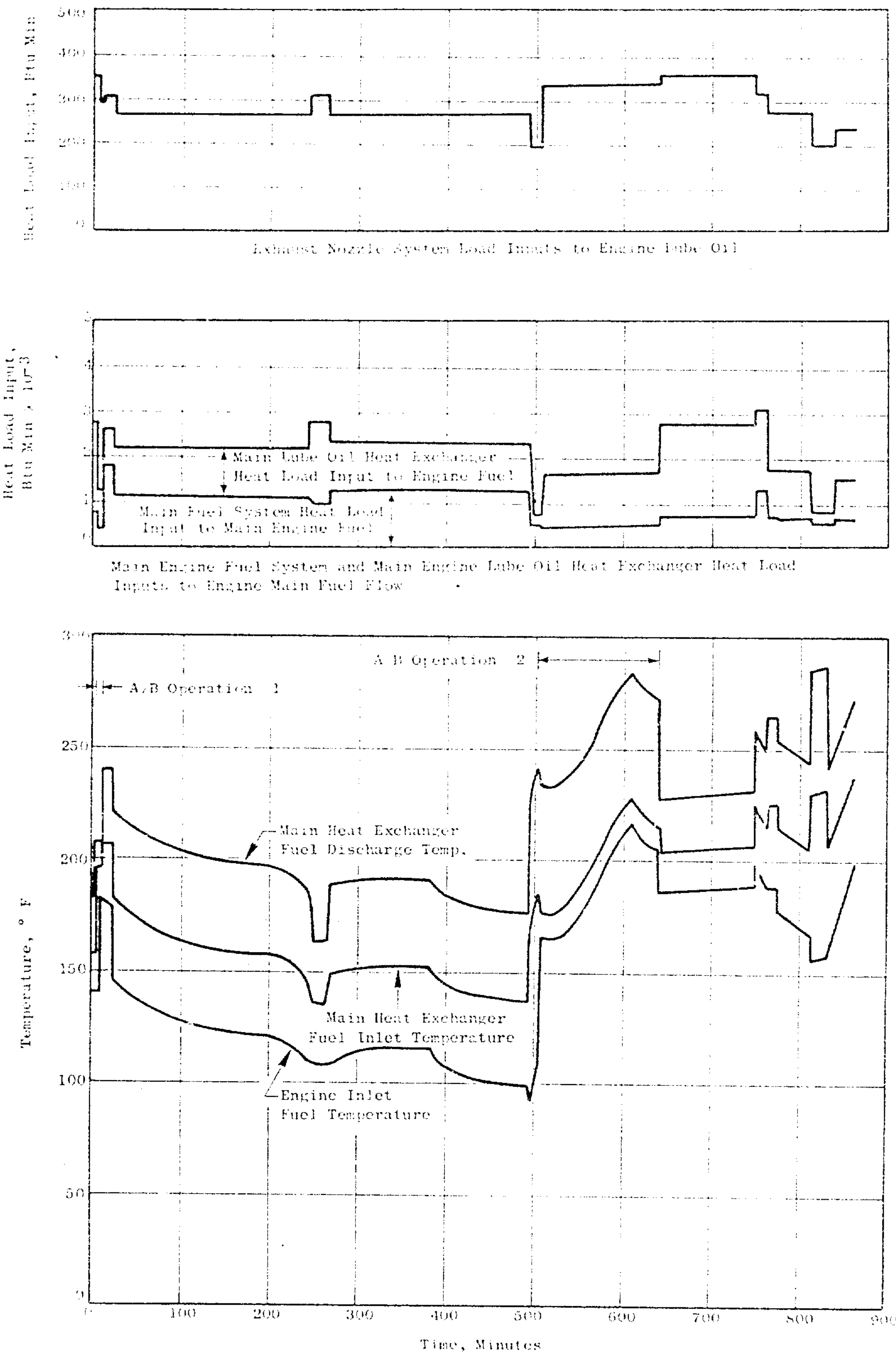


Figure 41. F101 Engine Heat Load Inputs to Engine Fuel and Fuel Temperature Changes During Subsonic Mission.

Figure No. 42 shows the F101 main engine heat loads transferred to the fuel during the supersonic mission and the resulting main engine fuel temperature changes. The continuous plots as shown on Figure 42 are for the heat loads and resulting fuel temperature changes in the fuel flow to the main engine combustor. However, during periods of afterburner operation, the afterburner fuel flow has a heat load input to the afterburner fuel from pumping heat loads. Also, the afterburner fuel flow provides additional heat sink for the engine lube oil in the afterburner heat exchanger.

During afterburner operation, the afterburner fuel system has the following effects on engine fuel flow:

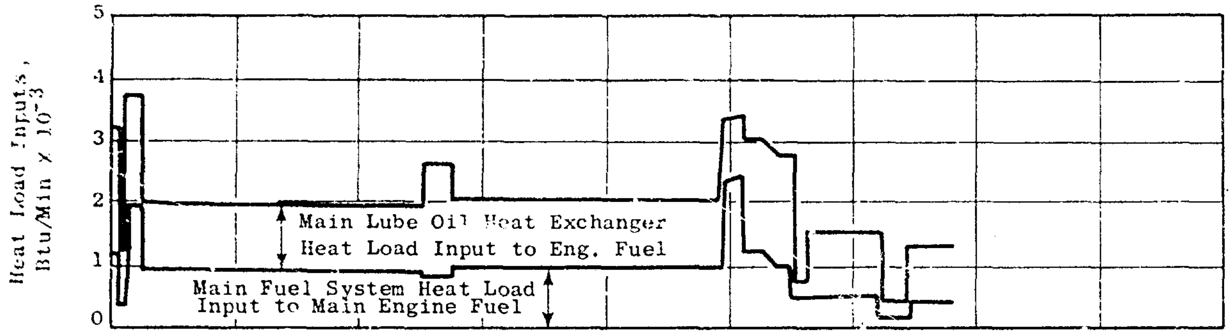
AFTERBURNER OPERATING POINT
(Shown on Figure 42)

Heat Load/Fuel Temperature*	1	2	3	4
A	693	4640	6050	5200
B	1565	2052	1776	1776
C	138	58	93	106
D	143	69	110	123
E	155	116	162	175

*Same definitions as for subsonic mission.

An advanced aircraft design (10), with a sustained supersonic mission, is represented by the data plots on Figures 43 and 44. The heat load transferred to the fuel during flight and the resulting fuel temperature rise (using present primary-type JP-4/JP-5 fuel and MIL-L-27502 lube and hydraulic oil) are shown on these two figures.

The aircraft boost pump, electrical, hydraulic, and environmental systems heat loads rejected to the fuel (as shown on Figure 43) reach a total level of approximately 15,000 Btu/min during the aircraft mission. These heat loads result in a temperature rise in the engine fuel as shown on Figure 32. At the end of the supersonic portion of the mission the temperature of fuel at the engine inlet is 223° F as shown on Figure 32. At this point the aircraft began idle descent to subsonic cruise altitude. At the initiation of idle descent, the fuel flow demand of the engine is at a low level while the aircraft heat loads are reduced at the rate the aircraft approached subsonic cruise altitude. During this time period the fuel temperature at the engine inlet is limited to 250° F. Fuel recirculation to the aircraft fuel tank is required in this portion of the mission resulting in a sharp increase (from 120° to 131° F) in the fuel in the aircraft tank. The final peak in engine inlet fuel temperature to 250° F is during the final idle descent for landing.



Main Engine Fuel System and Main Engine Lube Oil Heat Exchanger
Heat Load Inputs to Engine Main Fuel Flow

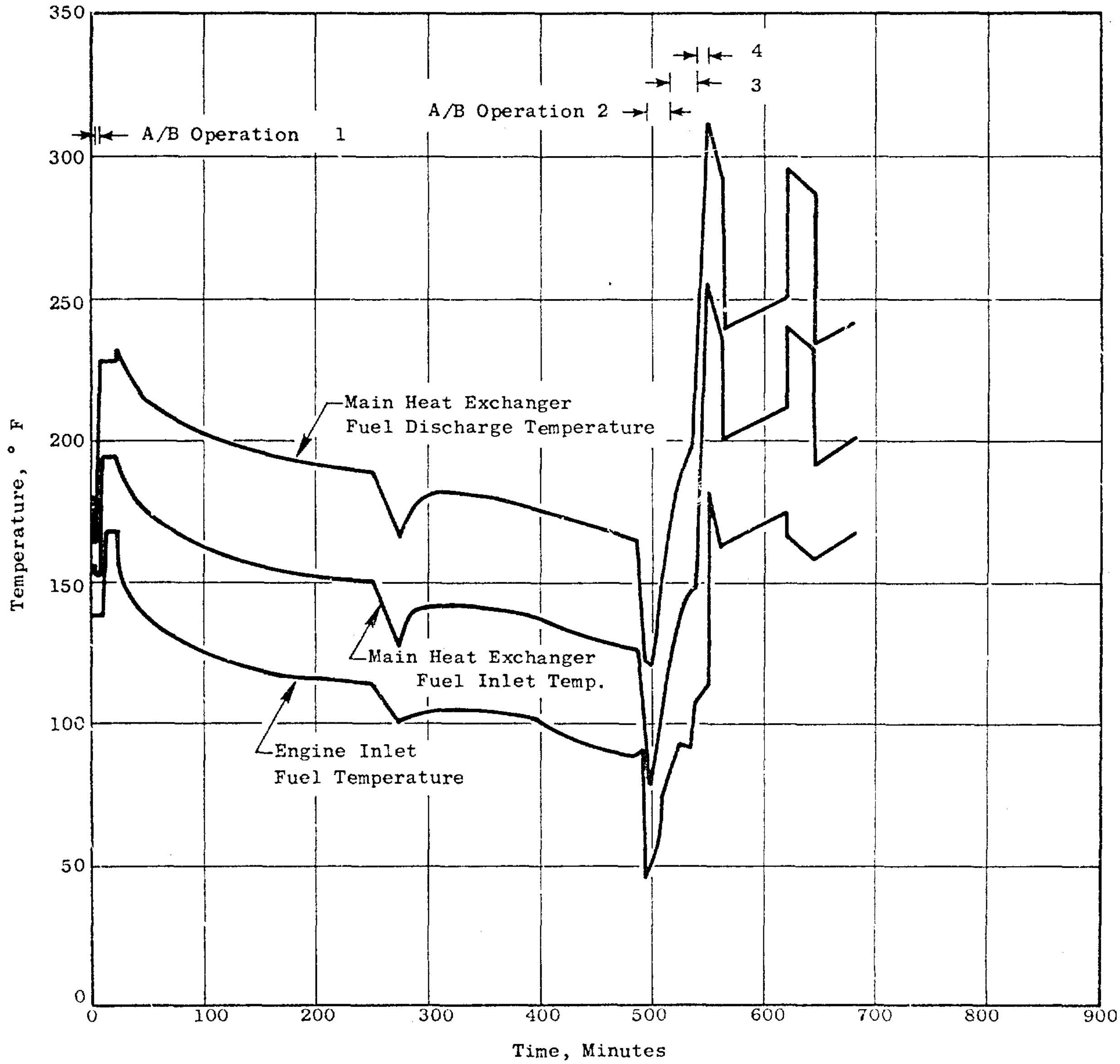


Figure 42. F101 Engine Heat Load Inputs to Engine Fuel and Fuel Temperature Changes During Supersonic Mission.

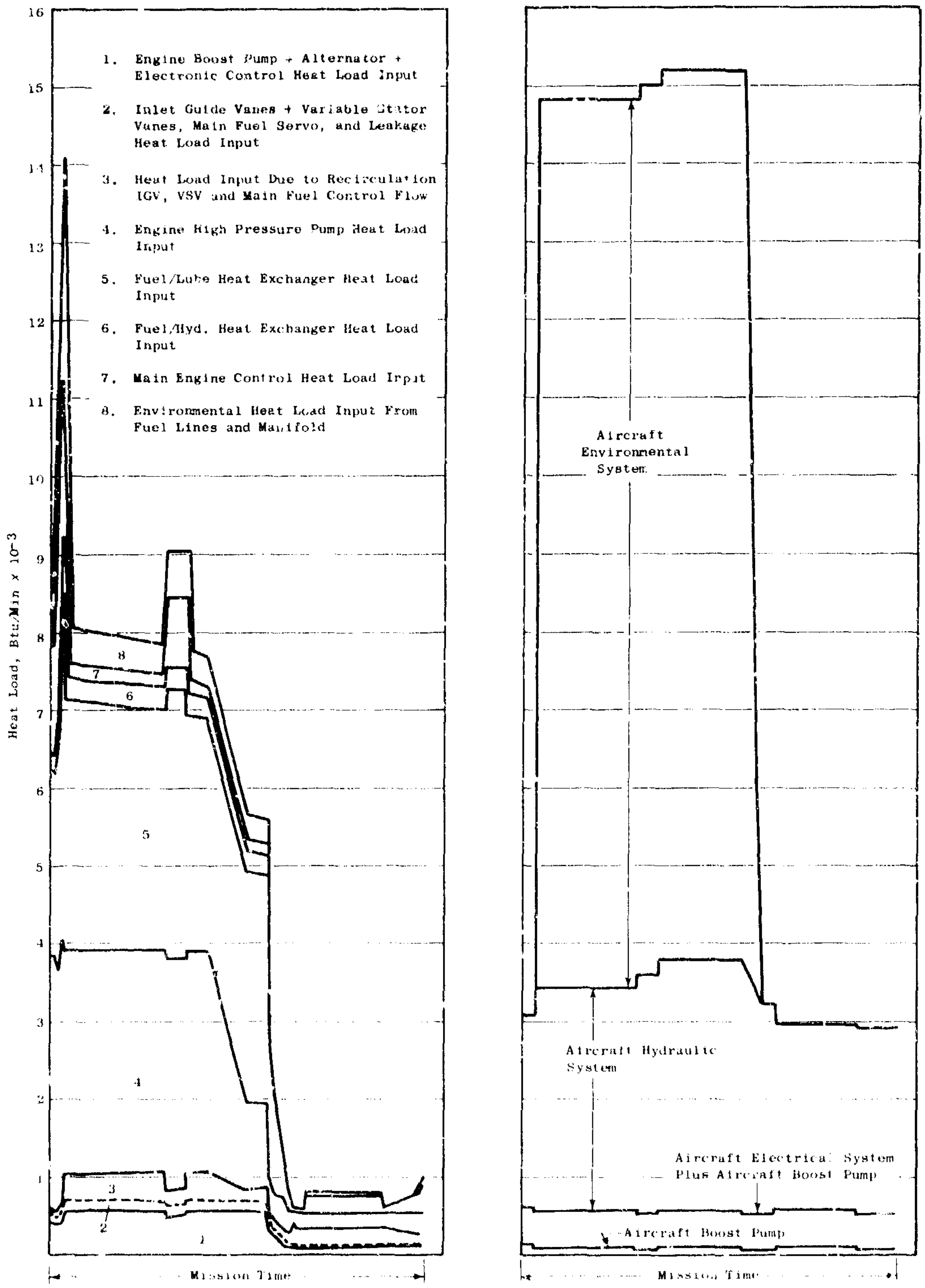


Figure 43. Advanced Supersonic Aircraft and Engine Heat Load Inputs to Engine Fuel.

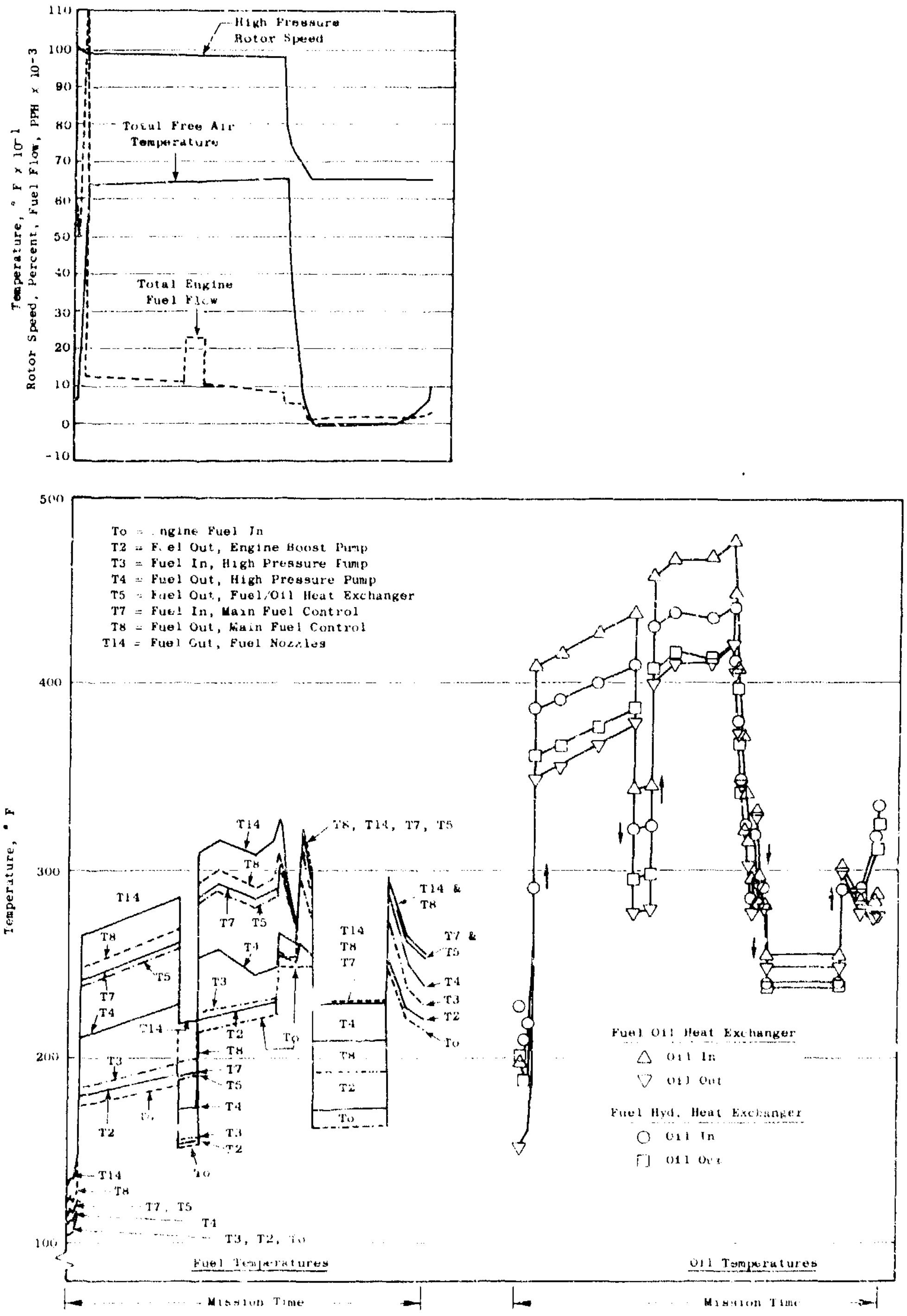


Figure 44. Advanced Supersonic Aircraft and Engine Fuel Temperature Changes.

The engine heat loads transferred to the engine fuel, as shown on Figure 43, represent the engine component or system heat loads from the engine boost pump to the engine combustor. The fuel temperature changes resulting from these heat loads are shown on Figure 44 along with the oil-in and oil-out temperature for the engine fuel/oil and fuel/hydraulic heat exchanger.

SECTION VI

HEAT SINK UTILIZATION

This section presents a review of the aircraft and engine heat loads as they effect the total fuel system temperature levels. Fuel management techniques developed for fuel heat sink utilization are discussed. A review of the heat loads from aircraft and engine systems is made with emphasis on establishing the magnitude of these generated heat loads.

Fuel management for heat sink utilization has been a key consideration on several aircraft designs including the XB-70A, the U.S. Supersonic Transport, and an advanced supersonic aircraft. For these three aircraft the flight condition where fuel temperatures generally reach maximum values is in the initial idle descent portion of the flight at the end of supersonic cruise. At this point aircraft system heat loads are at or near maximum, aerodynamic heating effects on aircraft fuel have reached peak values, and fuel flow to the engine is at minimum for the flight condition. Continuing flight for this time-limited idle descent phase would result in fuel temperatures exceeding thermal stability limit unless provisions for temperature control are provided.

The XB-70A[9] aircraft has 11 integral fuel tanks located 1 through 5 in the fuselage (1 being forward) and 6 through 8 in the wing (6 being forward). The fuel tanks were constructed primarily of honeycomb sandwich panels which reduce the aerodynamic heating effects on the fuel. Tank number 3 is the common sump tank for the aircraft.

Figure 45 indicates the approximate fuel management utilized for a sustained supersonic flight. The wing fuel tanks are the fastest heating tanks from an aerodynamic heat standpoint due to the high ratio of surface to volume. Therefore, wing tank No. 6 is the first tank to empty and eliminates 60% of the fuel in the wing tanks during takeoff and initial climb. Wing tanks Nos. 7 and 8 are held full until later in the mission to provide more favorable center-of-gravity control and flight stability. These are the smallest tanks in the aircraft and, therefore, prolonged aerodynamic heating does not adversely affect the overall heat sink capacity.

Temperatures were recorded in tanks number 1 and 7 during the sustained supersonic flight. The maximum temperature in tank number 1 was 118° F and occurred as the tank went empty. The initial fuel temperature in tank number 1 was 70° F. Tank number 1 is a fuselage tank and has a relatively low surface-area-to-volume ratio; the 48° F temperature rise during the flight was due primarily to aerodynamic heating. The maximum temperature in wing tank number 7 was 108° F as the tank went empty. Tank number 7 has a relatively high surface-area-to-volume ratio. During the initial climb to cruise, the average rate of fuel temperature rise in tank number 1 was calculated to be approximately 0.105° F per minute; and, in tank number 7, it was 0.702° F per minute. During the Mach 3 cruise portion of the flight the average rate of temperature rise in tank number 1 was calculated to be approximately 1.9° F per minute.

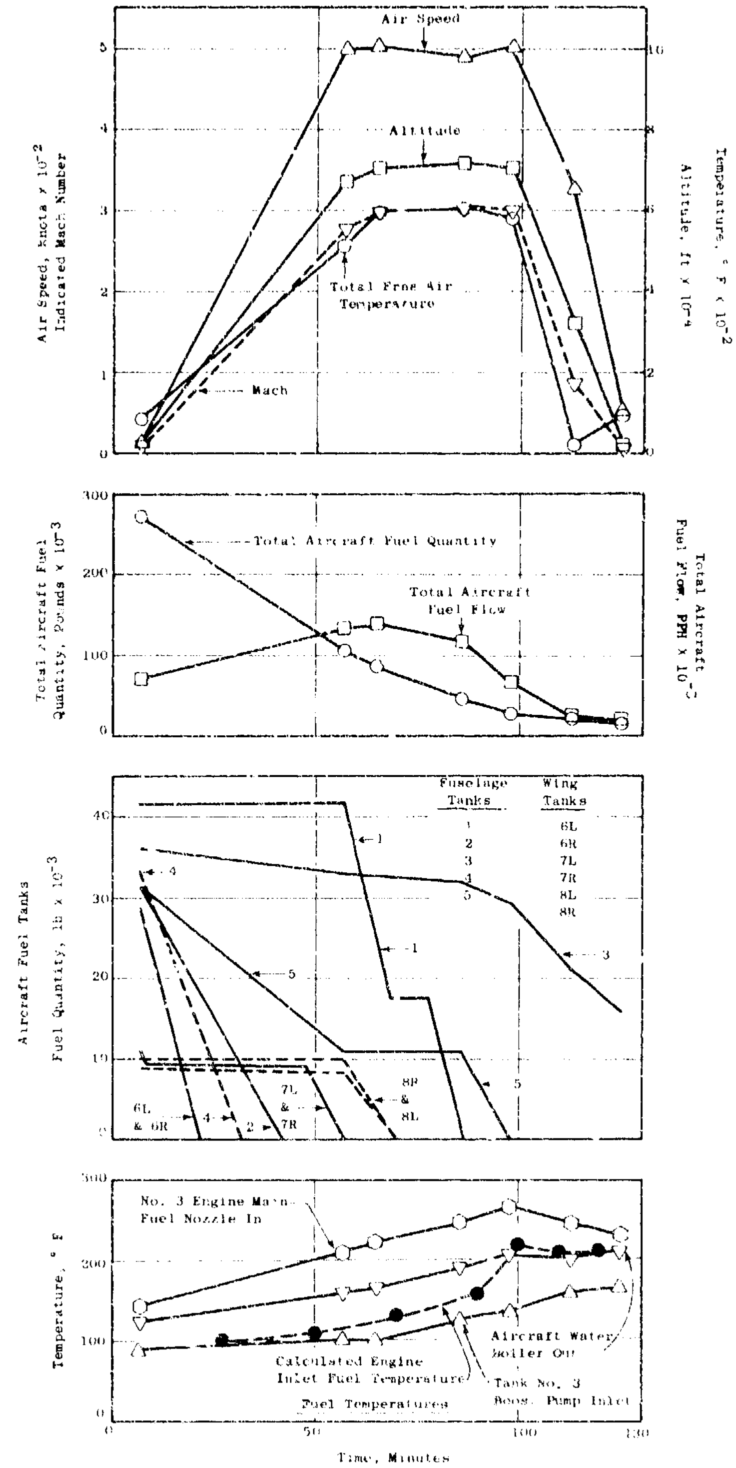


Figure 45. XB-70A Fuel Management in Flight.

These data indicate the difference in heating rates for different tank configurations and the necessity of fuel management for fuel heat sink utilization.

The XB-70 aircraft utilizes the aircraft supply fuel as the heat sink for various air vehicle subsystems. The fuel heat sink coolant loop located in tank 4 is essentially parallel to the engine's supply system and contains heat exchangers for cooling the landing gear and drag chute, each of four hydraulic systems, and six accessory drive systems. These heat exchangers are arranged with the system of lowest temperature first, progressing to the system with highest temperature last in the fuel coolant loop.

Design fuel flow through the coolant loop varies between approximately 655 and 785 pounds per minute depending upon engine demand and corresponding system back pressure. The aircraft coolant loop supplies the total flow to the engine unless the engine demand is greater than the coolant loop flow. If engine demand is greater than coolant loop flow, the additional flow is supplied through the main engine supply line; and, if engine demand is less than coolant flow, the excess flow is returned to the sump tank.

The engine fuel temperature inlet limits are 300° F for cruise and 260° F for idle power descent. During idle descent, the engine fuel flow drops below coolant flow; however, the aircraft heat loads do not decrease appreciably until the aircraft decelerates below Mach 1.5. To meet the 260° F engine fuel inlet temperature limit during initial idle descent, a water boiler is included in the aircraft fuel coolant loop.

The U.S. Supersonic Transport (SST) was designed to operate at sustained supersonic cruise. The aerodynamic heating encountered by the SST required that both aircraft and engine systems rely heavily upon the fuel heat sink to control system temperatures. The aircraft fuel (i.e., fuel flow to the engine) was the primary heat sink for cooling purposes for the SST. During a typical flight [11] the increase in fuel temperature due to aerodynamic heating of aircraft fuel tanks, combined with increase in fuel temperature due to aircraft and engine systems heat loads, resulted in a fuel temperature at the engine combustor approaching the 325° F limit for kerosene fuel at the end of cruise.

At the end of cruise during initial idle descent, the aircraft system heat loads are at or near maximum; aerodynamic effects on aircraft fuel have reached peak values; and, fuel flow to the engine is at a minimum. Continuing flight would result in exceeding the thermal stability limits of the fuel and provisions for fuel temperature control were required. The fuel temperature control system for the SST was a recirculating fuel system. At the end of cruise, prior to retard to engine idle power, a selector valve on the flight deck is moved to "descent" position. This action results in the selector valve in the engine fuel system rerouting the metered fuel flow around the engine heat exchangers directly to the engine fuel nozzles. During this same time period, a portion of the fuel flow from the engine main fuel pump is directed by the selector valve through the engine fuel/oil cooler and recirculated to the aircraft fuel tank. This recirculation system was designed through cooperation

between the aircraft/engine fuel system designers and provides a means of avoiding fuel overtemperature during the low fuel flow conditions of idle descent after end of cruise.

The advanced supersonic aircraft[10], as discussed in this report and as represented by the fuel temperature and heat load plots of Figures 43 and 44, utilizes aircraft fuel as a heat sink to the extent that fuel temperature to the engine combustor is in the range of 265° to 325° F during a major portion of the flight.

As shown on Figure 44 the fuel temperature to the fuel nozzles reaches the 325° F thermal stability limit during the initial idle descent phase of the flight. This is due to the aircraft heat loads being at or near maximum, the aerodynamic effects on aircraft fuel being at peak values, and fuel flow to the engine being at a minimum for idle descent. To hold the temperatures level of 325° F to the engine combustor, fuel recirculation to the aircraft tanks is required. This recirculation fuel flow results in a fuel temperature increase of approximately 10° F in the aircraft fuel tank as shown on Figure 32.

This recirculation system was designed through cooperation between the aircraft/engine fuel system designers and provides a means of avoiding fuel overtemperature during low fuel flow conditions of idle descent after end of cruise.

Heat loads from aircraft and engine systems and components are real and are established. The data plots of fuel temperatures and heat loads in Section V show that aircraft heat-load demands on fuel heat sink have increased significantly from present operational aircraft such as the F-4 to aircraft designs such as the XB-70A, the B-1, and the advanced supersonic aircraft.

The major aircraft heat load sources are the aircraft electrical, hydraulic, and environmental systems. These heat loads vary depending upon flight conditions as shown in the data plots in Section V. The maximum aircraft heat loads range from approximately 900 Btu/min/engine for the F-4C, to 4300 Btu/min/engine for the XB-70A, to 4850 Btu/min/engine for the B-1, and to 7600 Btu/min/engine for the advanced supersonic aircraft.

The major engine heat load sources are the engine fuel delivery and lubrication systems. The major contribution to the engine heat load in the fuel delivery system is the high-flow main fuel pump. Engine pumping capacity must be provided to handle the high flows of maximum power settings for takeoff and climb to cruise altitude.

The F-4C, XB-70A, and B-1 aircraft, as well as most presently operational aircraft, utilize a fuel bypassing-type main engine fuel control system. The engine receives fuel from the aircraft fuel tank boost pumps generally between 15 and 40 psia depending upon altitude. The main engine fuel pump then increases the fuel pressure to a level sufficient to overcome all system pressure losses and to inject the fuel into the engine combustor.

At altitude cruise condition, the fuel demand for the engine is significantly reduced, and excess flow capacity from the constant displacement gear pump in the fuel system results in temperature rise due to the excess capacity returned to the gear pump inlet. Figure 46 shows the general range of temperature rise for a bypassing-type engine fuel control system as a function of fuel system pressure level and percentage of bypass fuel flow.

The fuel supply system for the advanced supersonic aircraft is shown on Figure 47. This fuel system design is a single-pass system and supplies only that fuel flow required by the engine. A throttling-type fuel control was selected for this advanced engine design because of its high efficiency and low thermal input to the fuel. The fuel flow control system operates by throttling the flow and maintaining a fixed back pressure on the pumps.

The regenerative pump was selected because of its ability to supply relatively high pressure fuel at low shaft speeds and fuel flows during engine starts. The regenerative pump is similar to the centrifugal pump in construction, is lightweight, and can be flow regulated by throttling. The system is designed to utilize the regenerative pump only during engine starts. As engine speed approaches idle the shuttered centrifugal pump takes over; the inlet to the regenerative pump is shut off; and, the pump casing is drained.

The shuttered centrifugal pump was selected for the advanced engine design because of its broad flow turn-down ratio of 150:1 or greater. Since the major contril or to the use of the fuel heat sink in the fuel delivery system is the high-flow main fuel pump, utilization of the shuttered centrifugal pump design prevents excessive thermal stressing of the fuel during the cruise and idle descent portions of the mission. Closing of the shutter, at low fuel flows, prevents recirculation in the pump and, as a result, significantly reduces the power losses. Figure 48 shows the pump characteristics of the shuttered centrifugal fuel pump. By closing the shutter at flow rates below approximately 10% of maximum fuel flow, the major portion of the mission is spent in closed-shutter operation.

The afterburner fuel supply system designs for the F-4C, XB-70A, and B-1 aircraft utilize high pressure centrifugal pumps with throttling-type fuel controls. The afterburner pumps on the F-4C and XB-70A aircraft are single stage centrifugal pumps, while the afterburner pump for the B-1 aircraft is a shuttered centrifugal pump. During afterburner operation, the afterburner fuel flow (through an afterburner fuel/oil cooler) provides additional heat sink capacity for the engine. The fuel temperature rise in the engine afterburner fuel supply system is generally less than the fuel temperature rise in the main engine fuel supply system.

Engine lubricating system heat loads and the resulting changes in fuel temperatures are shown on the data plots in Section V. The engine lubricating system heat loads rejected to the fuel increase with increasing air speed at constant altitude and decrease with increasing altitude at constant air speed.

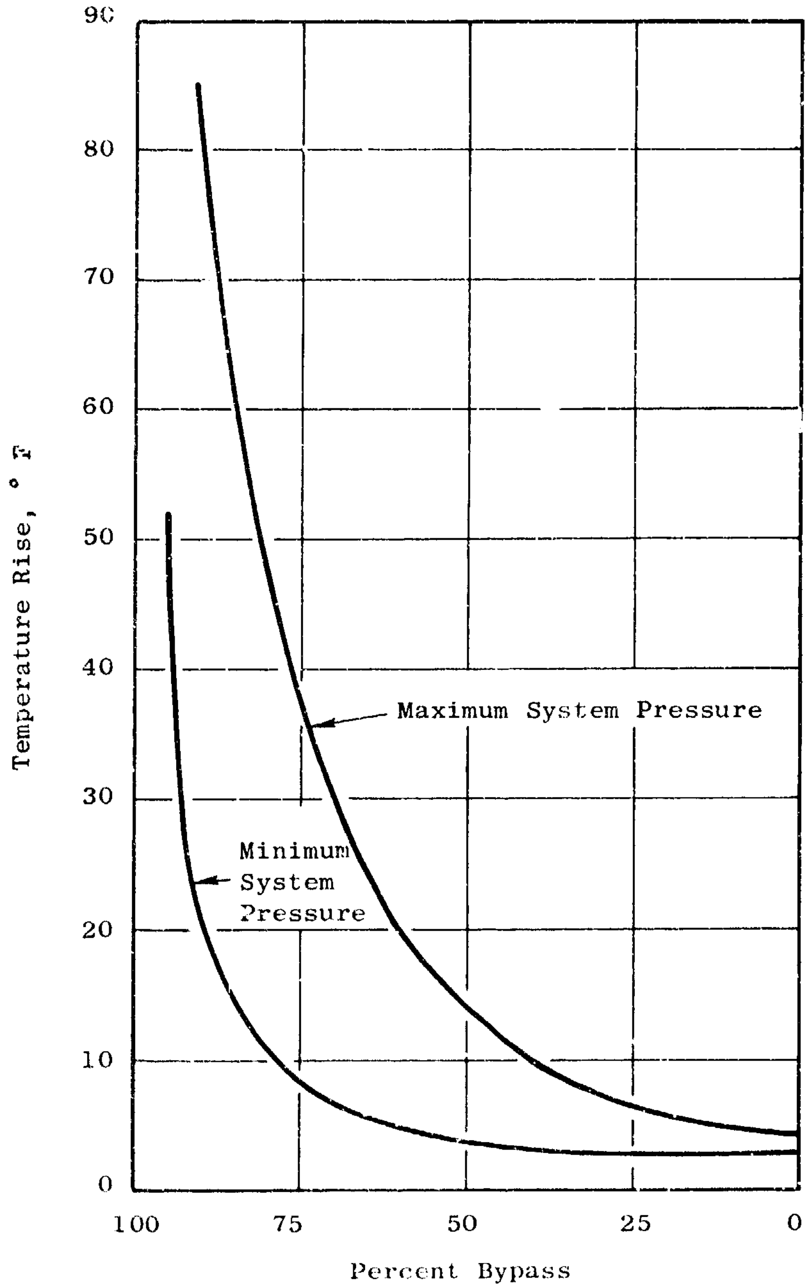


Figure 46. Typical Fuel System Temperature Rise as a Function of System Pressure and Percent Bypass Fuel Flow.

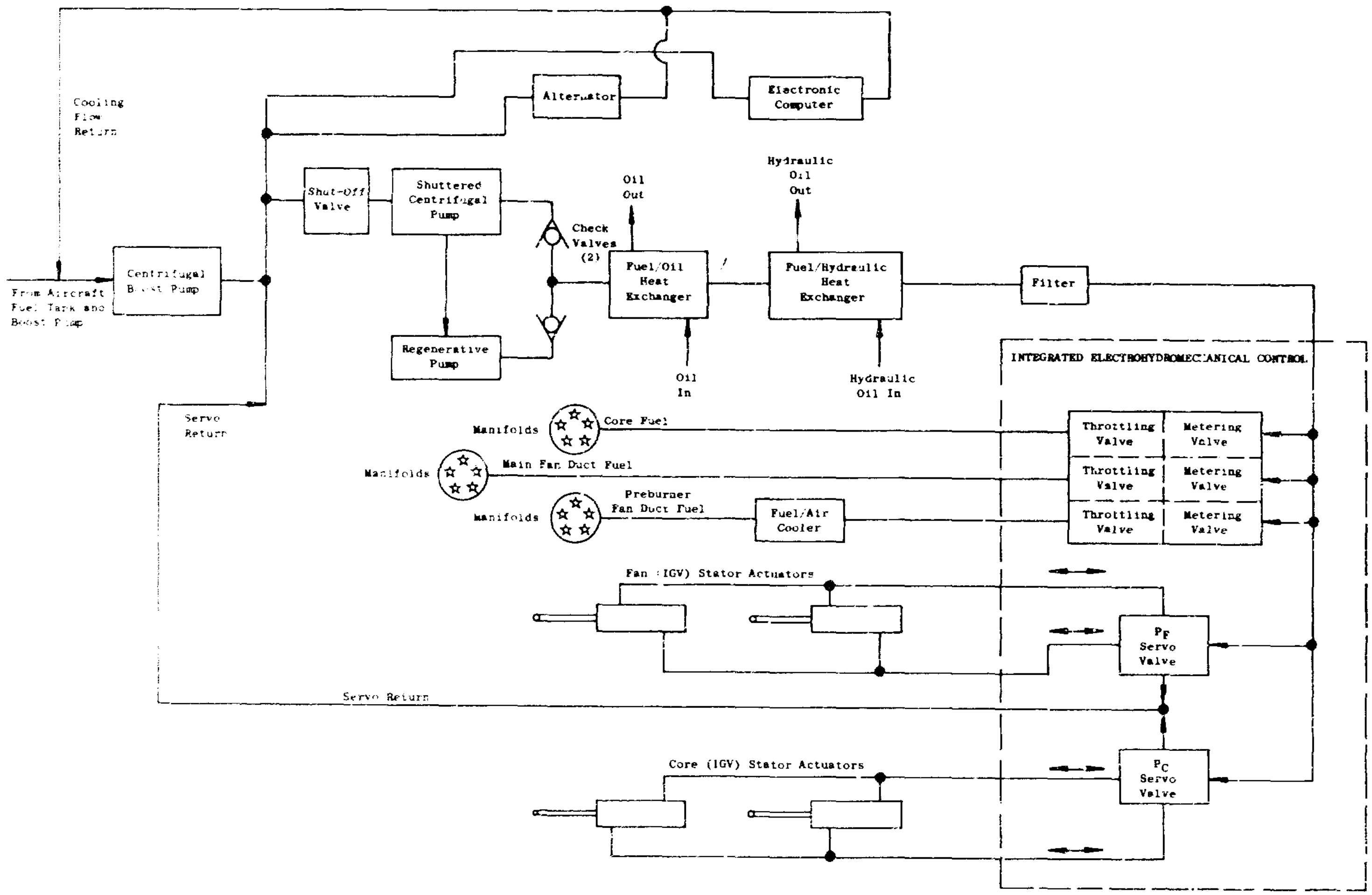


Figure 47. Advanced Supersonic Aircraft Fuel Delivery System Schematic.

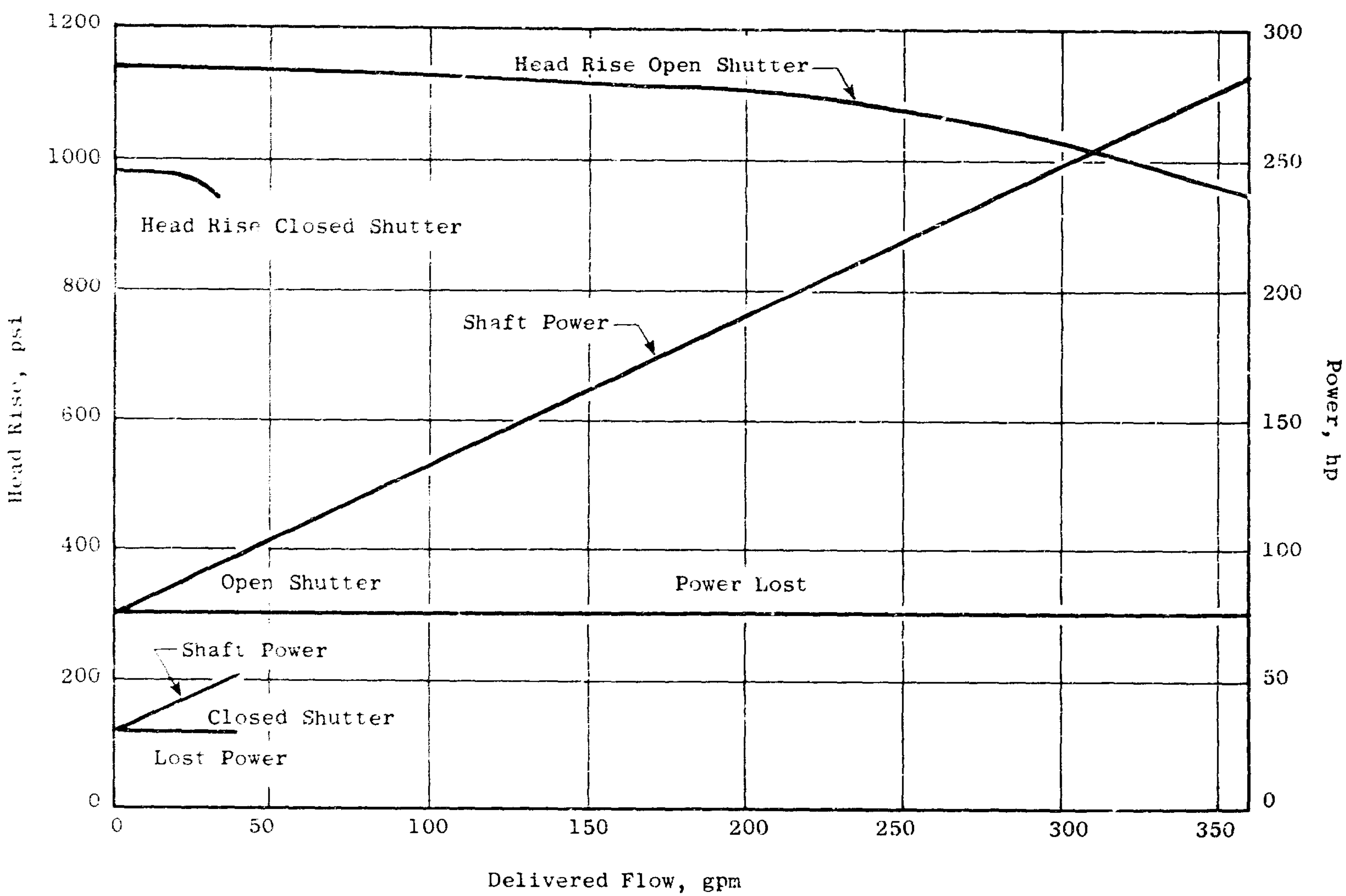


Figure 48. Shuttered Centrifugal Fuel Pump Characteristics.

The changes in engine lubricating system heat loads for the engines, as represented by the data plots in Section V, have unique characteristics with respect to engine power level and aircraft flight condition. Figure 49 shows these changes in heat loads for two of the aircraft for high and low altitude flights and increasing air speed with the subsonic cruise operating point as a baseline.

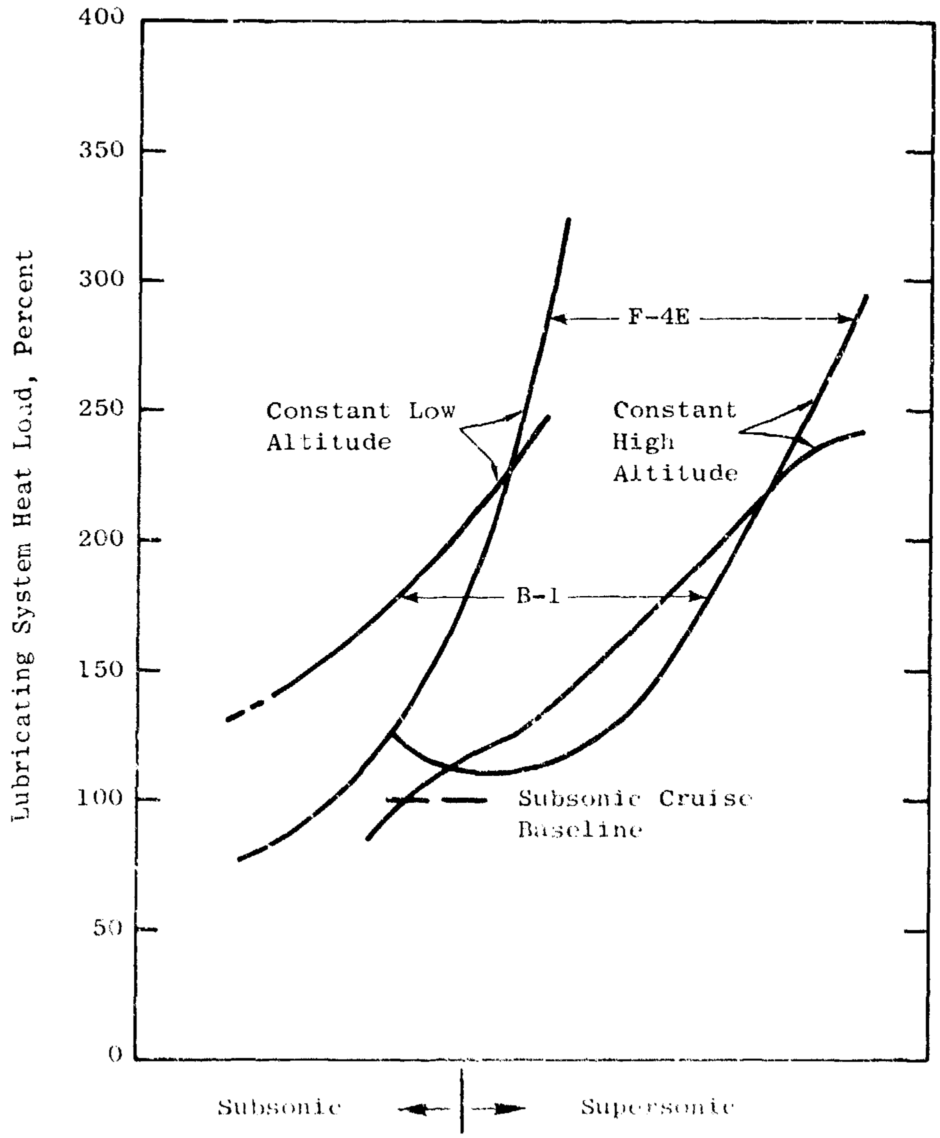


Figure 19. Changes in Engine Lubricating System Heat Load as a Function of Altitude and Air Speed.

SECTION VII

MINEX THERMAL STABILITY TESTS

This section presents the results obtained from MINEX thermal stability tests on fuel samples provided by the USAF. A total of 73 separate MINEX tests on 27 different fuel samples was completed. Changes or modifications to the test procedures and equipment, and the solutions to problems as the program progressed, are described in detail.

1. Description of Apparatus and Test Procedures

The MINEX is a device for measuring fuel thermal stability by determining the effect of fuel degradation products on heat transfer. Figure 50 is a photograph of the device. In operation, a fuel sample is pumped through the test section at a constant flow rate of approximately one quart per hour, and at a sufficiently high pressure to prevent vaporization.

The test section is made of stainless steel (type 321) tubing 57.1 inches long, 0.022 inch inside diameter, and 0.042 inch outside diameter. The walls are indented at regular intervals to promote turbulence. The tubing is formed into a series of loops to reduce the overall dimensions to approximately 9 inches long and 2 inches in diameter. The test section is supported within an evacuated chamber to minimize heat losses to the surroundings. Figure 51 is a schematic of the test section.

Fuel passing through the test section is heated by controlled direct current in the tube wall. At two places, immediately upstream and immediately downstream of the test section, the tubing is formed into closed loops which do not carry current; hence, the fuel is not heated electrically in these loops. Judicious placement of sensors on these loops permits measuring fuel temperature, since it is essentially identical to wall temperature at those locations. These fuel sensors are called "RF" ("reference fuel") temperature at the inlet of the measuring section, and "MF" ("maximum fuel") temperature at the exit of the measuring section.

The tubing between the two fuel loops is 15.7 inches long and comprises what is considered the measuring section. Near each end of this section are two additional sensors for measuring tube wall temperatures. These are called "RM" ("reference metal") temperatures at the inlet measuring section and "MM" ("maximum metal") temperatures at the exit of the measuring section.

When equilibrium is reached at constant MM temperature, the ΔT (MM - MF) is an indication of the heat transfer coefficient at that point. If this ΔT increases over a period of time (e.g., one to three hours), it indicates a film of "gum" is being deposited on the tube walls in the vicinity of the MM sensor.

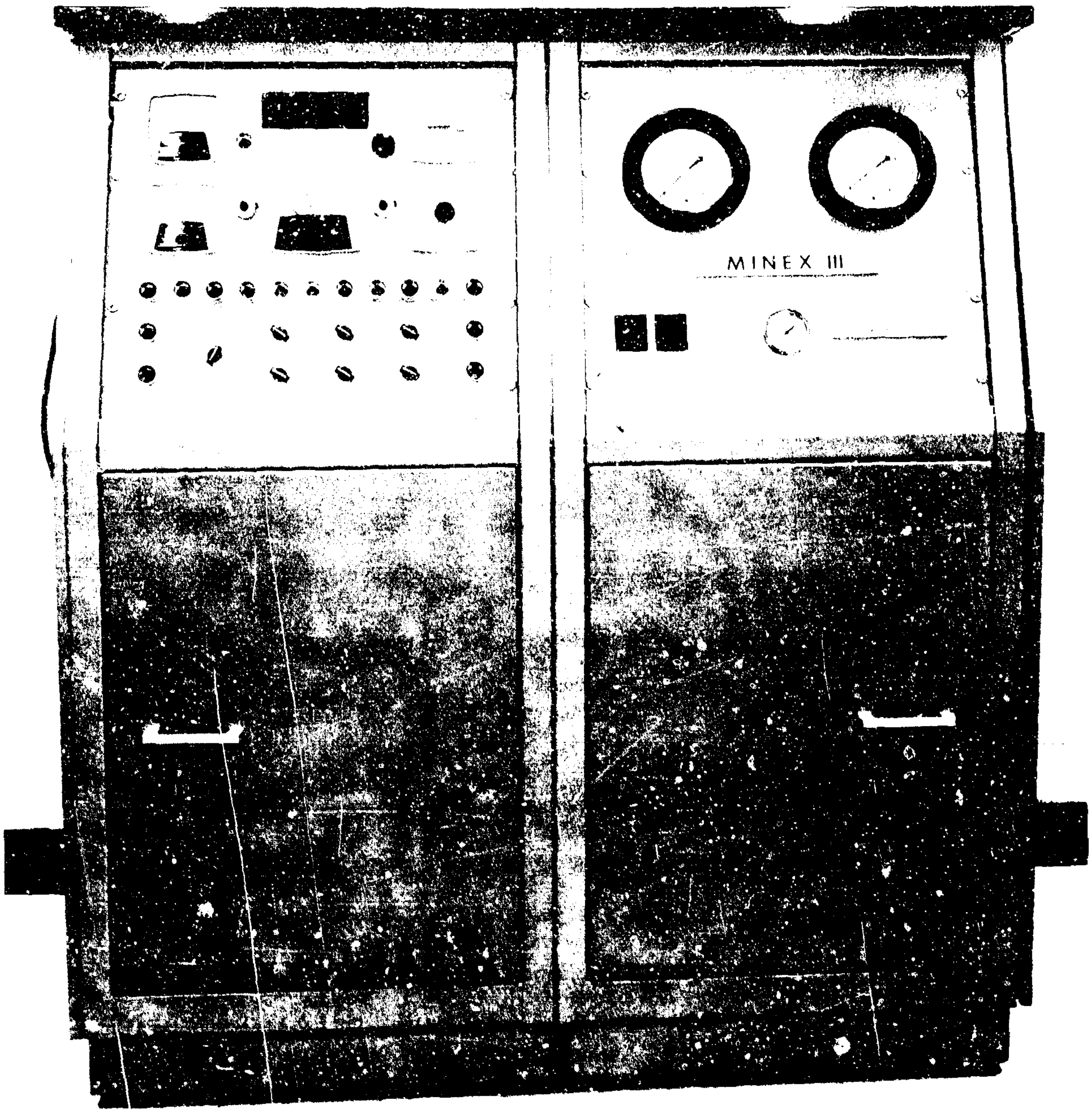


Figure 50. MINEX III Fuel Thermal Stability Tester.

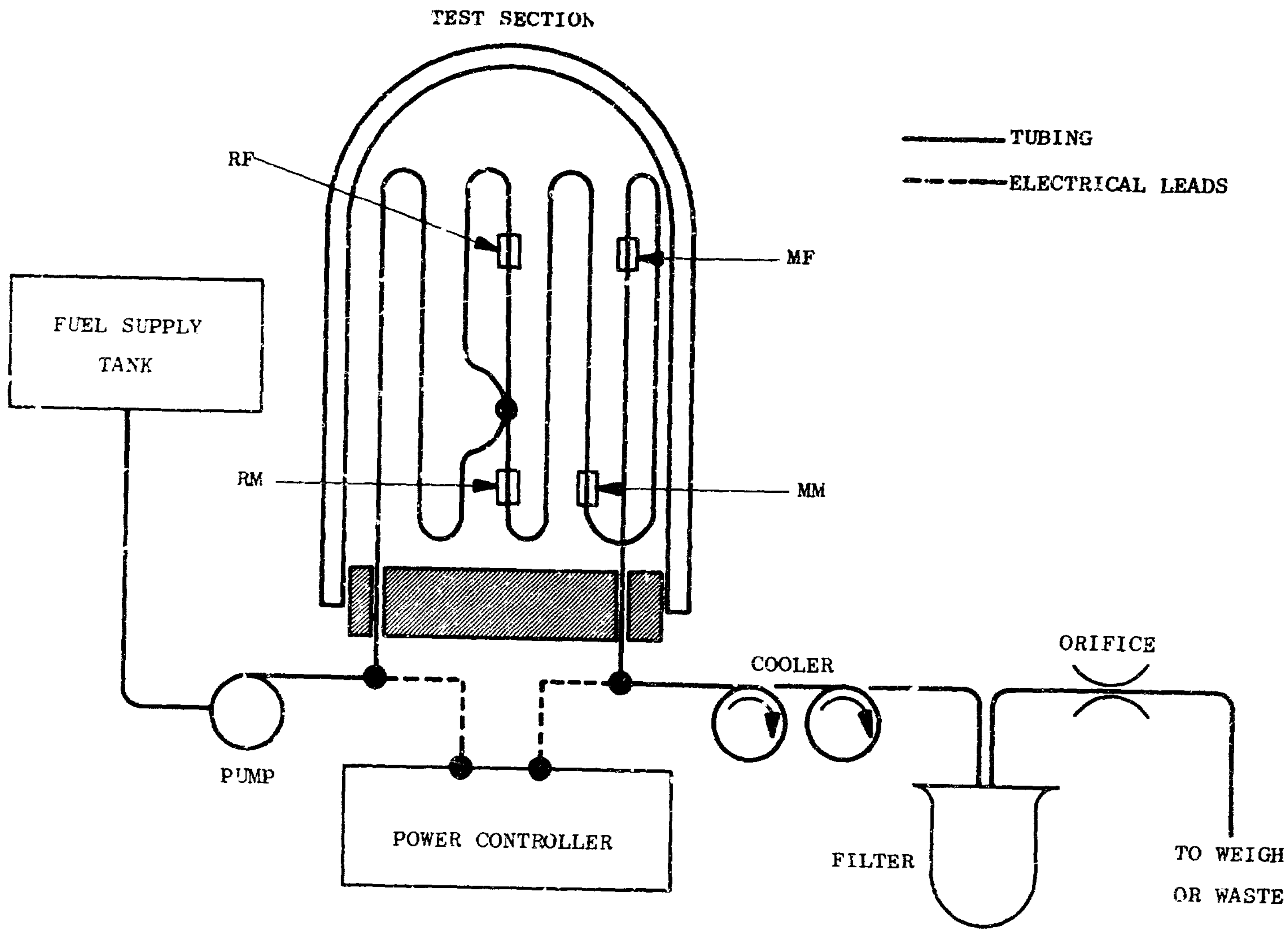


Figure 51. Schematic, MINEX Model III.

To expedite testing, the MINEX is normally run in a "Program Mode" in which MM is increased at a constant rate (normally 1° F per minute) to establish a dynamic, rather than a static, equilibrium. As the temperature level increases, so does the ΔT. Since this could be confused with the indication of gum deposites, a correction must be applied. This is the reason for the use of the RF and RM reference sensors.

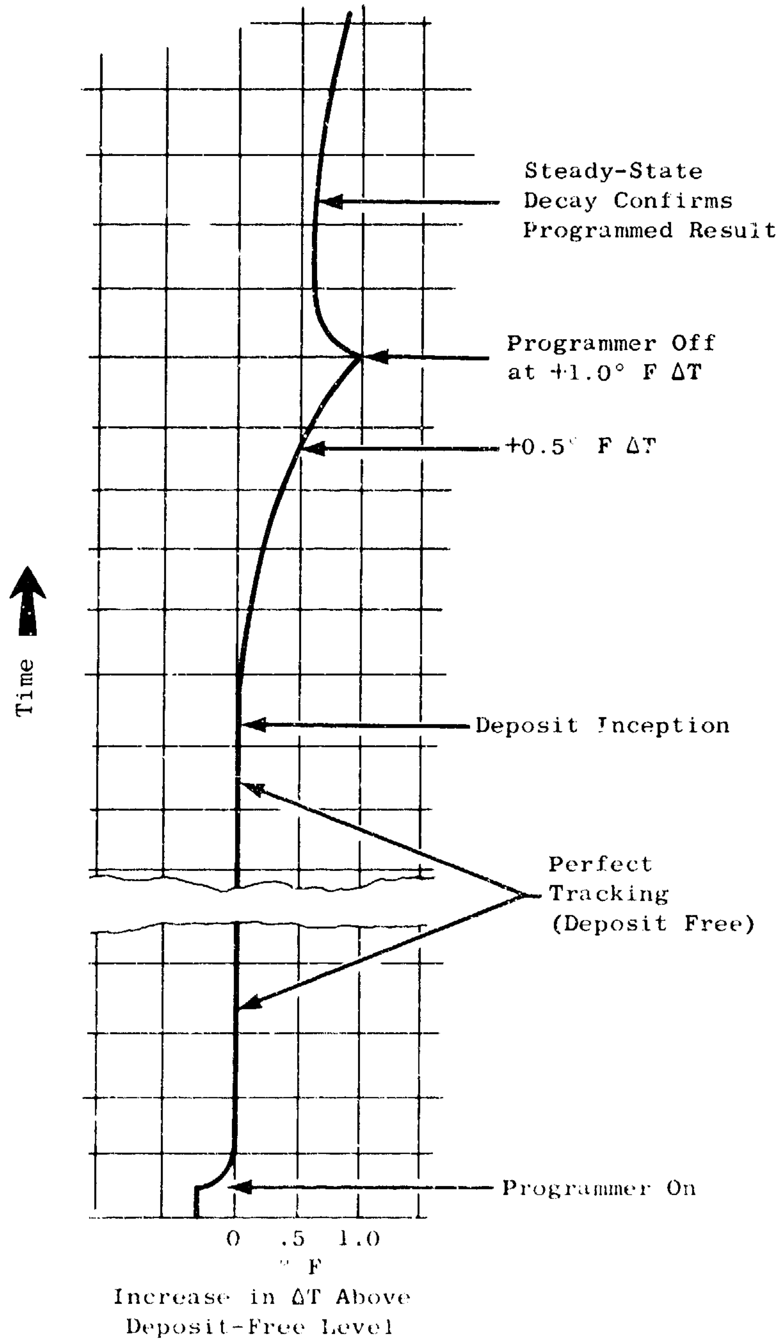
At the temperatures of the RM reference sensor, gum formation is delayed over an hour behind the time it occurs at the MM sensor, since the temperature at the RM sensor location is approximately 70° F lower than the MM sensor location. Since the heat transfer characteristics of fuels vary in an almost linear mode with temperature, over a 70° F span, the linearity can be considered exact. Therefore, a function of the reference ΔT (RM - RF) can be applied to the ΔT (MM - MF) to correct for the effects of scheduled temperature increases on MM - MF. In the MINEX III this correction is made electronically, so that movement of the deposit indicator to the right (up-scale) indicates the presence of gum deposits. During initial setup of the unit, a manual adjustment is required to be sure it is "tracking" properly (i.e., the needle holds steady while the temperature is rising through a range where no gum is forming).

The end point of this test has not yet been firmly established. Obviously it would be desirable to know the lowest temperature at which the first indication of gumming can be detected. Practically, this is very difficult to do, as it means determining the exact point (temperature) at which a straight line becomes a large-radius curve, as measured by the recorder trace of the position of the deposit indicator needle. Figure 52 represents an idealized example of a MINEX recorder trace which illustrates the previously mentioned problem. More practical end points are specific increments, such as a 0.5°, 1.0°, or 1.5° F increase in ΔT above the "zero" or gum-free value. Higher values are more readily related to temperature as the radius of curvature decreases (gumming rate increases). However, excessive gum deposits are undesirable because of possible difficulty in subsequent removal. Satisfactory compromise value may be +1° F ΔT increase for a rating point. This may be 60° to 70° F higher than the temperature at which the first deviation from a straight line recorder plot can be detected.

The MINEX deposit indicator can be set so that programming stops when a preset value of ΔT is reached, and the test continues at constant MM temperature. The rate at which ΔT increases at constant MM temperature can then be monitored. Since a ΔT increase indicates a decay in the heat transfer coefficient, this is commonly referred to as the "decay rate" and is expressed in ° F/hr. A significant decay rate, generally greater than 0.10, is proof that the preceding deflection of the indicator was caused by gum formation and not by some nonlinear signal output.

2. Operating Experiences

Most of the JP-4 samples were rated at several different increments of ΔT; but, for brevity, only the "Plus One" temperatures (+1° F increase in differential temperature above the deposit free level) are shown in Table III.



NOTE:

During Programmer Operation, MM Temperature Rises at 1° F per Minute.

Figure 52. Idealized Example of MINEX Recorder Tape.

Table III. MINEX Test Results.

Fuel Number	Test Date	Plus One Rating Temp, ° F	Decay Rate, ° F/hr	Comments
1	5/30	484*	---	Reversal ~ 0.75 (530° F).
1	6/15	491*	0.25 @ 491° F	Programmer off at 0.5. Result appears valid.
1-A	10/27	434	0.10 @ 434° F	Steady-state decay insignificant. Probably stable above 434° F.
2	6/2	499	0.07 @ 499° F	Steady-state decay insignificant. Probably stable above 499° F.
2	6/7	499	---	Probably stable above 499° F.
3	6/9	493*	---	Reversal ~ +0.75 (535° F).
3	6/13	493*	0.12 @ 493° F	Programmer off @ 0.5. Result appears valid.
4	6/19	459*	0.05 @ 459° F	Steady-state decay insignificant. Probably stable above 459° F.
4	6/21	469*	---	Probably stable above 469° F.
4	10/23	438	0 @ 438° F	No steady-state decay. Probably stable above 438° F.
4	10/24	425	0 @ 425° F	No steady-state decay. Probably stable above 425° F.
5	6/23	449*	0.84 @ 449° F	Unstable at 449° F, confirmed.
5	6/27	439*	0.75 @ 439° F	Unstable @ 439° F confirmed.
5	8/7	448*	0.78 @ 448° F	Unstable @ 448° F, confirmed.
6	6/29	481**	---	Reversal @ ~ +0.30 (515° F).
6	7/5	481**	0.06 @ 481° F	Programmer off @ 0.25. Steady-state decay insignificant. Probably stable above 481° F.
6	10/31	430	0.06 @ 430° F	Steady-state decay insignificant @ 430° F. Possibly unstable @ 454° F.
6	10/31	430	0.13 @ 454° F	---
6-A	11/2	434	0 @ 434° F	No steady-state decay @ 434° F, insignificant @ 468° F. Probably unstable @ 468° F.
6-A	11/2	434	0.13 @ 468° F	---
6-A	11/8	449	0.45 @ 449° F	Unstable @ 449° F, confirmed.
6-A	11/10	419	0 @ 419° F	No steady-state decay. Probably stable above 419° F.
7	7/7	472*	0 @ 472° F	No steady-state decay. Probably stable above 472° F.
7	8/1	492	0 @ 492° F	No steady-state decay. Probably stable above 492° F.
7-A	11/15	447	0.05 @ 447° F	Steady-state decay insignificant. Probably stable above 447° F.
7-A	11/17	453	0 @ 453° F	No steady-state decay. Probably stable above 453° F.
8	8/3	>500	Unmeasureable	Reversal @ ~ +0.40 (504° F).
8	8/9	>511	Unmeasureable	Reversal @ 0 (512° F).
8	9/12	>510	0.94 @ 547° F	Reversal @ ~ 0.25 (530° F).
8	9/14	>518	0.92 @ 537° F	Reversal @ ~ 0 40 (532° F).
8-A	11/21	452	0.14 @ 452° F	Steady-state decay insignificant. Probably stable above 452° F.
8-A	11/24	448	0 @ 448° F	No steady-state decay. Probably stable above 448° F.
9	9/27	485	1.36 @ 485° F	Unstable @ 485° F, confirmed.
9	9/29	481	1.53 @ 484° F	Unstable @ 484° F, confirmed.
10	10/5	511	0 @ 511° F	No steady-state decay. Probably stable above 511° F.
10	11/14	437	0 @ 470° F	No steady-state decay. Probably stable above 470° F.
11	10/9	537	0.78 @ 537° F	Unstable @ 537° F, confirmed.
11	10/11	523	0.76 @ 523° F	Unstable @ 523° F, confirmed.
12	10/13	505*	0.68 @ 547° F	Reversal @ ~ +0.60 (540° F). Unstable @ 547° F, confirmed.
12	10/17	494*	0.47 @ 547° F	Reversal @ ~ +0.70 (543° F). Unstable @ 547° F, confirmed.
13	11/28	461	0.10 @ 461° F	Steady-state decay insignificant. Probably stable above 461° F.
13	11/29	459	---	None
14	12/1	462	0.10 @ 462° F	Steady-state decay insignificant. Probably stable above 462° F.
14	12/4	460	---	None.
15	12/6	462	0.01 @ 481° F	Steady-state decay insignificant. Probably stable above 481° F.

11	10/9	537	0.78 @ 537° F	Unstable @ 537° F, confirmed.
11	10/11	523	0.76 @ 523° F	Unstable @ 523° F, confirmed.
12	10/13	506*	0.68 @ 517° F	Reversal @ ~ +0.60 (540° F). Unstable @ 547° F, confirmed.
12	10/17	494*	0.47 @ 547° F	Reversal @ ~ +0.70 (543° F). Unstable @ 547° F, confirmed.
13	11/28	461	0.10 @ 461° F	Steady-state decay insignificant. Probably stable above 461° F.
13	11/29	459	---	None
14	12/1	462	0.10 @ 462° F	Steady-state decay insignificant. Probably stable above 462° F.
14	12/4	460	---	None.
15	12/6	462	0.04 @ 481° F	Steady-state decay insignificant. Probably stable above 481° F.
15	12/7	469	---	None.
16	12/11	464	---	None.
16	12/19	459	0.21 @ 490° F	Unstable @ 459° F. Confirmed @ 490° F.
17	1/5/73	448	0.30 @ 477° F	Unstable @ 448° F. Confirmed @ 477° F.
17	1/8	447	---	None.
18	1/15	446	0.07 @ 477° F	Steady-state decay insignificant. Probably stable above 477° F.
18	1/18	442	---	None.
18	1/24	449	---	None.
19	1/26	432	0.07 @ 461° F	Steady-state decay insignificant. Probably stable above 461° F.
19	2/6	420	---	None.
TF-7	2/8	426	0.09 @ 458° F	Steady-state decay small. Result appears valid.
TF-7	2/12	423	---	None.
TF-8	2/14	412	0.13 @ 441° F	Steady-state decay small. Result appears valid.
TF-8	2/15	411	---	None.
TF-9	2/19	410	0.34 @ 437° F	Unstable @ 410° F. Confirmed @ 437° F.
TF-9	2/20	406	---	None.
TF-10	2/22	416	0.24 @ 443° F	Unstable @ 416° F. Confirmed @ 443° F.
TF-10	2/23	400	---	None.
TF-10	2/26	402	---	None.
20	2/27	404	0.41 @ 432° F	Unstable @ 404° F. Confirmed @ 432° F.
20	2/28	401	---	None.
20	3/6	417	---	None.
21	3/8	397	0.13 @ 427° F	Steady-state decay small. Result appears valid.
21	3/12	397	---	None.
22	3/15	398	0.08 @ 417° F	Steady-state decay small. Result appears valid.
22	3/16	438	---	Poor check of preceding run. Reason unknown.
22	3/19	406	---	None.
22	3/20	406	---	None.
AF-88	3/22	404	0 @ 422° F	No steady-state decay. Probably stable above 425° F.
AF-88	3/23	403	0.12 @ 436° F	Steady-state decay small. Probably unstable @ 436° F.
EVENDALE PLANT JP-4 SAMPLES				
6/22	9/5	490	0.75 @ 490° F	None
8/9	9/7	476	2.43 @ 476° F	Highest steady-state decay rate ever observed.
8/9	9/8	474	2.43 @ 474° F	Repeat test @ 30 psi higher pressure. Excellent check
9/22	10/3	490	1.59 @ 490° F	None.
12/12	12/13	461	0.20 @ 497° F	None.
12/14	12/21	455	0.42 @ 487° F	None.

* Rated at +0.50 rather than at +1.0 because of reversal.

** Rated at +0.25 rather than at +1.0 because of reversal.

-A indicates new sample.

Among the first dozen fuels supplied, most would not run to a "Plus One" indication before the deposit indicator would reverse and start going downscale. This had never occurred before, and the reason was at first obscure. However, it was concluded that at the high temperatures reached, most of these JP-4 fuels began to vaporize, and the resultant nucleate boiling over-compensated for the effects of the gum deposits. At this time, normal operating pressure was around 450 psi, and the equipment was not capable of much higher pressures. Consequently, new gages and valves were ordered to allow increased pressures. Meanwhile, tests run at the limit of existing equipment confirmed that higher pressures would overcome the problem.

When the new parts were received and installed, normal operating pressure was increased to 700-750 psi. All subsequent tests were run at these pressures; and, since that time, there have been no reversals of the deposit indicator, thus apparently verifying the theory that nucleate boiling was being encountered earlier.

Since the results of some of the early tests were questionable because of the reversals, it was considered desirable to repeat them. Unfortunately, residual samples were not retained following the tests. However, the Air Force had some additional samples on hand, and these were rerun at pressures over 700 psi.

The rating temperatures of these latter tests were lower than those obtained originally, based on operation in the program mode. However, since subsequent steady-state operation showed insignificant decay or no decay, it must be concluded that the rating obtained in the program mode was not valid, and the fuel was more stable than indicated. Hence, the apparent increase in ΔT must have been caused by some nonlinearity in the signal output rather than by deposition of fuel gum.

A second problem appeared at this time when it was found that one fuel (TF-9) showed instability as soon as the programmer was turned on, and before tracking could be established. Consideration of the circumstances indicated that hot recirculation was the probable cause.

In order to generate good data with the MINEX, thermal equilibrium must be established as quickly as possible. This presupposes a constant fuel flow rate. It is recognized that the fuel flow rate will decrease slightly as the fuel supply pump oil temperature rises. To assure a steady-state oil temperature, the operating procedure included a one-hour warm-up period before a test was begun. Additionally, to conserve fuel, recirculation was used; and, to further assure test section warm-up, an MM temperature of 300° F was maintained. As the experience with fuel TF-9 showed, this was too close to the temperature at which fuel instability could be encountered. The operating procedure was therefor modified; and, in all subsequent tests, the one-hour recirculation was conducted with the fuel at room temperature.

3. Test Results

Tests were run on 27 JP-4 samples submitted by the Air Force. A total of 73 tests was conducted. The results are tabulated in Table III. As a matter of interest, tests run on 6 samples of JP-4 from the Evendale Plant supply, during the same time period, are included for comparison.

4. Summary of Test Results

The most reliable thermal stability ratings obtained in the program mode are those which are subsequently confirmed by steady-state decay. These are listed below. The numbers in parentheses following the rating temperature indicate the number of test results used in establishing the average.

In the early part of the program, many fuels were rated at 0.5 rather than 1.0 to avoid reversal. Since the difference between 0.5 and 1.0 has been found to average 21° F, this value has been added in some cases to secure "Plus One" ratings for comparison. The ratings so obtained are indicated by an asterisk.

Fuel No. 8 did not yield a definite rating. However, a practical value was obtained by averaging the highest temperature obtained (500° F) before reversal began, and the higher temperatures (537° and 547° F) at which steady-state decay was obvious.

The fuels are listed in decreasing order of stability:

Fuel Number	Plus One Rating Temp., ° F
11	530 (2)
8	522 (2)
12	521 (2)
3	514* (1)
1	512* (1)
9	485 (2)
5	466* (3)
16	462 (2)
6-A	449 (1)
17	448 (2)
TF-7	425 (2)
TF-8	412 (2)
22	412 (4)
TF-9	408 (2)
20	407 (3)
TF-10	406 (3)
21	397 (2)

* 21° F added to 0.5 rating to obtain Plus One rating.

It should be noted that the maximum fuel temperature that can be tolerated for long-time operation is much lower than the "Plus One" rating temperature, which indicates significant gum deposits in very brief test intervals.

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS - TANK FUEL TEMPERATURES AND HEAT SINK UTILIZATION

This section includes the conclusions and recommendations resulting from the review and analysis of the data as presented in Sections II through VI relative to changes in fuel temperature levels from ground bulk storage to engine combustor.

1. Conclusions

a. The results of the fuel storage and handling survey show a low incidence of on-loaded aircraft fuel above 95° F. This indicates that fuel temperature as loaded into aircraft fuel tanks could be established at some level below 95° F for a major portion of aircraft refueling periods.

b. The results of the survey relating to aircraft on standby, alert, or readiness simulated by fuel temperature changes under hot and cold soak environments show that fuel temperatures in aircraft fuel tanks are influenced by the initial fuel temperature and the local ambient temperature. For F-series aircraft in a hot desert environment, the fuel temperature in wing tanks follows closely the cyclic and magnitude changes in local ambient temperature, while the fuel temperatures in fuselage or trap tanks lag and are generally seven or more degrees F below maximum local ambient temperature. For B- and C-series aircraft, the results show that the fuel temperature in wing tanks requires from 25 to 50+ hours of exposure to static ambient temperatures 50° to 60° F above or below the initial fuel temperature before the fuel reaches a temperature level approaching the static soak temperature.

c. Flight profile effects on fuel temperature in aircraft fuel tanks are a function of the take-off fuel temperature and the resulting free stream total temperature. The heating rate in the number 1 fuselage fuel tank of the XB-70A was an average of 1.9° F per minute at sustained Mach 3 flight, while the initial cooling rates in wing tanks of F-series aircraft were as high as 3° to 4° F per minute for initial large differences in wing tank fuel temperature and free stream total temperature.

d. Heat loads from aircraft and engine components and systems are real and are established. Aircraft heat load demands on fuel heat sink have increased 5 to 8 times over present operational aircraft, such as the F-4, to aircraft designs such as the B-1 and advanced supersonic aircraft. This increased utilization of aircraft fuel as a prime heat sink for aircraft systems will require fuel system design and design for thermal integration in future aircraft and engine systems.

2. Recommendations

a. Since on-loaded aircraft fuel temperature is generally below 95° F for a major portion of aircraft refueling periods, precooling of fuel on the ground should be considered for future high performance aircraft designs for improvements in aircraft fuel heat sink utilization.

b. Fuel management for future aircraft should be used to provide improvements in aircraft fuel heat sink utilization by utilizing the heating or cooling rates of fuel in aircraft fuel tanks in the design of the fuel transfer systems.

c. For short time-limited periods (i.e., idle descent at end of supersonic cruise) fuel recirculation to the aircraft fuel tanks should be utilized to hold fuel temperatures at acceptable levels for aircraft and engine components.

SECTION IX

CONCLUSIONS AND RECOMMENDATIONS - MINEX THERMAL STABILITY TESTS

This section includes the conclusions and recommendations from the MINEX thermal stability tests on fuel samples supplied by the USAF.

1. Conclusions

a. Based on the most reliable and consistent data obtained, covering 17 fuels, the range of thermal stability of JP-4 fuels was found to be 133° F (530° F high, 397° F low). As a matter of interest, it may be noted that comparable tests performed in an earlier program on 14 commercial aviation kerosenes from world-wide sources showed a range of thermal stability of 129° F (589° F high, 460° F low).

b. About two-thirds of the samples tested have lower thermal stability than the JP-4 available at Evendale, and one-third have higher thermal stability.

c. Fuels differ markedly in deposit-forming rate versus temperature. Therefore, thermal stability rating methods that assign a single rating number to fuels (e.g., "Plus One" and "Code 3 Breakpoint" temperatures), fail to recognize this important difference in fuel capability.

d. A test pressure over 700 psi is required to suppress boiling in many JP-4 fuels heated to over 500° F.

2. Recommendations

a. Since fuel recirculation will probably be used for heat sink utilization in future aircraft, an experimental program should be established to evaluate its effects on fuel thermal stability.

b. Tests should be conducted to establish the relationship between fuel thermal stability ratings (single temperature values) and the rate of fuel degradation at constant temperature.

SECTION X

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13. ABSTRACT: This report identifies fuel temperature levels and contributors to fuel temperature rise or decrease at each step of fuel handling or usage from ground bulk storage to engine combustor. The program consisted of a literature search and review of available information on fuel temperatures in bulk storage and on-loaded aircraft tanks, flight profile effects on fuel tank fuel temperature, and fuel temperature changes resulting from aircraft and engine heat loads in flight. The study program was supplemented by MINEX thermal stability tests on JP fuels by the USAF. The results indicate a low incidence of bulk storage or refueling fuel temperatures above 95° F. Aircraft wing tank fuel temperatures, in static ground soak and in flight, follow closely the changes in local ambient or free stream total temperature. Fuselage or body tank fuel temperatures in static ground soak or in flight, have a gradual change with respect to large differences in local ambient or free stream temperature. The sources and levels of heat loads from aircraft and engine are established. Fuel temperatures are significantly influenced by the power requirements, the environment, and the design for thermal integration of the engine and aircraft fuel systems. The results of the MINEX thermal stability tests show a wide range in relative quality level for the fuels tested. The overall results indicate that aircraft and engine systems can be designed to operate in the Mach 3 range using present primary type fuels and state-of-the-art fluid system components. Heat loads must be established in the early stages of conceptual design, making aircraft fuel heat sink utilization a key consideration in the design of future high performance aircraft.

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